GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 11/17/80

Project Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Co- Project No: E-21-E22/E-19-E22 (Sub-projects under E-21-E00/Paris/EE)

S

Co- Project Director: Dr. E.B. Joy and Dr. R. F. Hochman

Sponsor: Naval Coastal Systems Center; Panama City, FL 32407

Agreement Period: From 9/9/80 (Delivery Order Term) Until ~~10/30/81~~ 12/31/81

Type Agreement: Contract No. N00612-79-D-8004, Delivery Order No. HR-22

Amount:
$38,019 E-21-E22
$81,837 E-19-E22
$119,856 TOTAL

Reports Required: Bimonthly Status Reports; Final Report

Sponsor Contact Person (s):

Technical Matters	Contractual Matters (thru OCA)
Max Weber Code 721 Naval Coastal Systems Center Panama City, FL 32407	Office of Naval Research Resident Representative 206 O'Keefe Building Georgia Institute of Technology Atlanta, GA 30332

NOTE: Follow-on to E-21-E01/E-19-E01

Defense Priority Rating: DO-C9 under DMS Reg. 1

Assigned to: Electrical Engineering/Chemical Engineering (School/~~XXXXXXX~~)

COPIES TO:

Project Director	Library, Technical Reports Section
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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

2-18-7/83

SPONSORED PROJECT TERMINATION SHEET

Date 6/7/82

Project Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Co-**Project No:** E-19-E22 (Co-project E-21-E22/Joy/EE; Subprojects under E-21-E00/Paris/EE)

Co-**Project Director:** Dr. R.F. Hochman

Sponsor: Naval Coastal Systems Center, Panama City, FL

Effective Termination Date: 12/31/81

Clearance of Accounting Charges: 1/31/82

Grant/Contract Closeout Actions Remaining:

See closeout actions for co-project E-21-E22.

- [ ] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: Chemical Engineering (School/~~Laboratory~~)

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Computer Input
Project File
Other ______

FORM OCA 10:781

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 6/7/82

Project Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Co- Project No: E-21-E22 (Coproject E-19-E22/Hochman/ChE;Subproject under E-21-E00/Paris/EE)

Co- Project Director: Dr. E.B. Joy

Sponsor: Naval Coastal Systems Center; Panama City,FL

Effective Termination Date: 12/31/81

Clearance of Accounting Charges: 1/31/82

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice ~~and Closing Documents~~
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [x] Govt. Property Inventory & Related Certificate
- [x] Classified Material Certificate
- [ ] Other ____________

Assigned to: Electrical Engineering (School/~~Laboratory~~)

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Other ____________

FORM OCA 10:781

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

A high current minesweeping electrode system including an S-cable, Anode and Cathode have been computer modeled and verified using previously obtained data. The computer model is being upgraded to include transient heating. Transient heating will occur either when the electrode current is pulsed or when the cable is moved slowly through the water. The later problem is more difficult as the heat flow analysis includes convection as well as conduction. A new parameter called thalpence must be determined for the analysis of the convective heat flow. Progress has been made on the transient heat flow and several working models have been developed. The most accurate models however require alot of computer time and require determination of approximately 300 eigenvalues to the Bessel heat flow equation prior to running the program. This two step process and lengthy computation time make this method of analysis bulky in carrying out parametric evaluations of the electrode system. Work is now underway to approximate the heat flow equation by a finite difference equation and solve it digitally.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

The transient heat flow analysis will continue, culminating in an efficient, accurate computer model for the transient heat flow from minesweeping system S-cables, anodes and cathodes.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date:	$ 1,725.63
This Two Month Period:	1,725.63
Funds Remaining:	36,293.37
Percent of Funds Expended:	4.5%
Percent of Task Completed:	4.5%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

The following are results obtained from a computer simulation of an example minesweeping system using conducting jacket anode and cathode. Table I. is a list of specifications for the electrodes.

Using an electrode length of 110 meters, Figure 1 and Figure 2 show the temperature and resistance as a function of aluminum area.

Figure 1 shows that at least 3.3 million circular mills of conductor area is needed to keep the hottest temperature of both the anode and cathode under 100 degrees celsius.

Figure 3 shows that the change in temperature is minimal as the conductor length is varied.

Figure 4 shows that a conductor length of at least 110 meters is needed to keep the total resistance under 15 milliohms.

Figure 5 and 6 show the temperature and resistance of 4 different jacket thicknesses as the jacket electrical conductivity is varied while the conductor area and conductor length were fixed at 3.3 million circular mills and 110 meters respectively. The figures show that a jacket electrical conductivity greater than 0.5 mhos/meter is desired.

Figure 7 and 8 show the temperature and resistance for 4 different jacket thicknesses as the jacket thermal conductivity is varied while the conductor area and length are fixed at 3.3 million circular mills and 110 meters, respectively.

It can be seen that a jacket thermal conductivity greater than about 2.8 milliwatt/cmC° is desired to keep the temperature lower than 100°C and the resistance lower than 15mΩ for the given range of jacket thicknesses.

TABLE I. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	10.541 cm (4.150 inches)
Length	110 meters (360.9 ft)
Maximum Current	≥8500 amperes
Maximum Temperature	≤100.0°C
Maximum System Resistance	≤15.0 milliohm
Bending Radius	≤3 feet
Core	
Material(s)	Heat resistant ABS and Silicone Foam
Diameter	8.260 cm (3.252 inches)
Thermal Conductivity	≥7.53×10^{-4} W/cm°C
Electrical Conductivity	≤10^{-5} mho/m
Specific Gravity	≤0.3
Core Sheath	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	6 mills
Thermal Conductivity	≥2.95×10^{-3} W/cm°C
Electrical Conductivity	≤10^{-5} mho/m
Specific Gravity	≤1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	≥2.36 W/cm°C
Electrical Conductivity	≥3.536×10^{7} mho/m
Thermal Coefficient	≤0.56%/C
Specific Gravity	≤2.7
Number of Conductors	56
Winding Pitch Angle	21.7°
Shape of Conductors	Round
Size of Conductors	29,464 CM
Percent Fill of Aluminum	74.9
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	≥2.95×10^{-3} W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	≤1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	6 mills
Thermal Conductivity	≥2.95×10^{-3} W/cm°C
Electrical Conductivity	≥.5 mho/m
Specific Gravity	≤1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	$\geq$2.36 W/cm°C
Electrical Conductivity	$\geq 3.536 \times 10^7$ mho/m
Thermal Coefficient	$\leq$0.56%/C
Specific Gravity	2.7
Number of Conductors	67
Winding Pitch Angle	21.7
Shape of Conductors	Round
Size of Conductors	24,627 CM
Percent Fill of Aluminum	74.6
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	$\leq$1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	6 mills
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	$\geq$0.5 mho/m
Specific Gravity	$\leq$1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	$\geq 2.8 \times 10^{-3}$ W/cm°C
Electrical Conductivity	$\geq$0.5 mho/m
Specific Gravity	$\leq$1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30°C
Thermal Conductivity	5.796×10^{-3} W/cm°C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

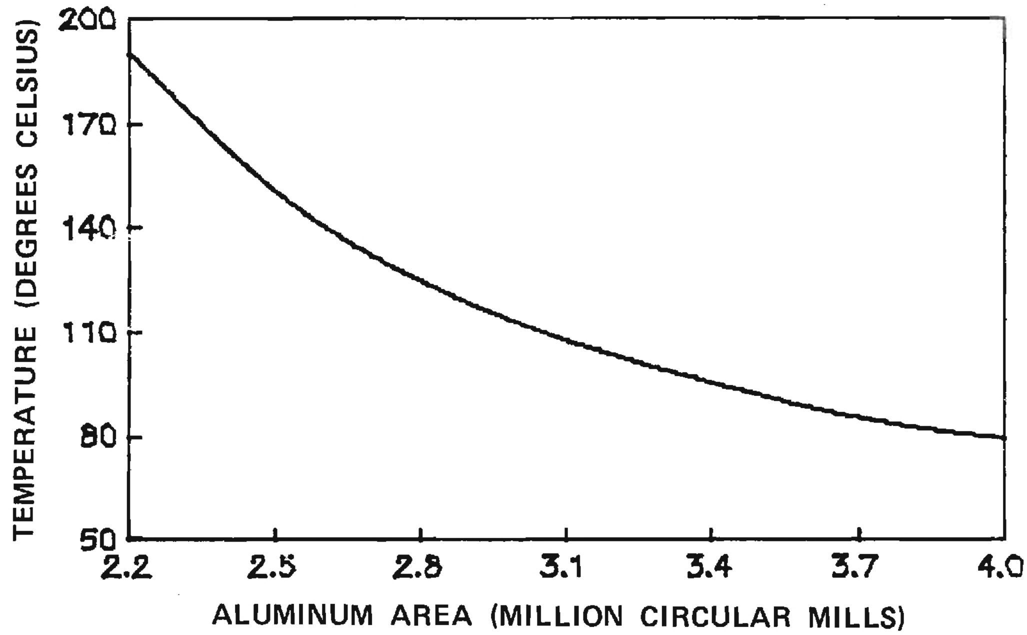


Figure 1. Electrode Temperature Versus Conductor Size

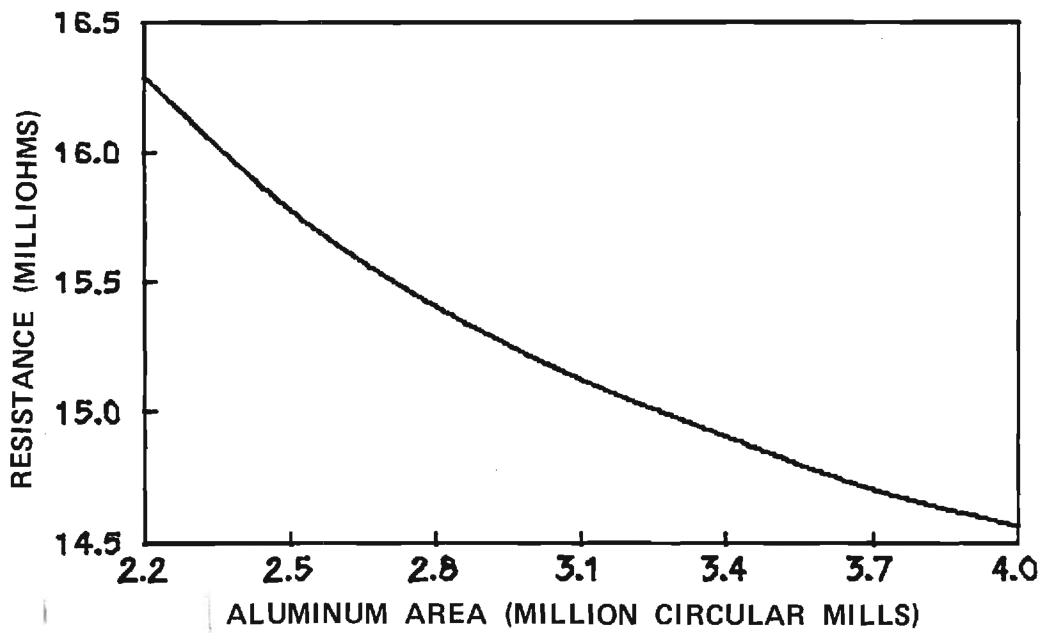


Figure 2. System Resistance Versus Electrode Conductor Size

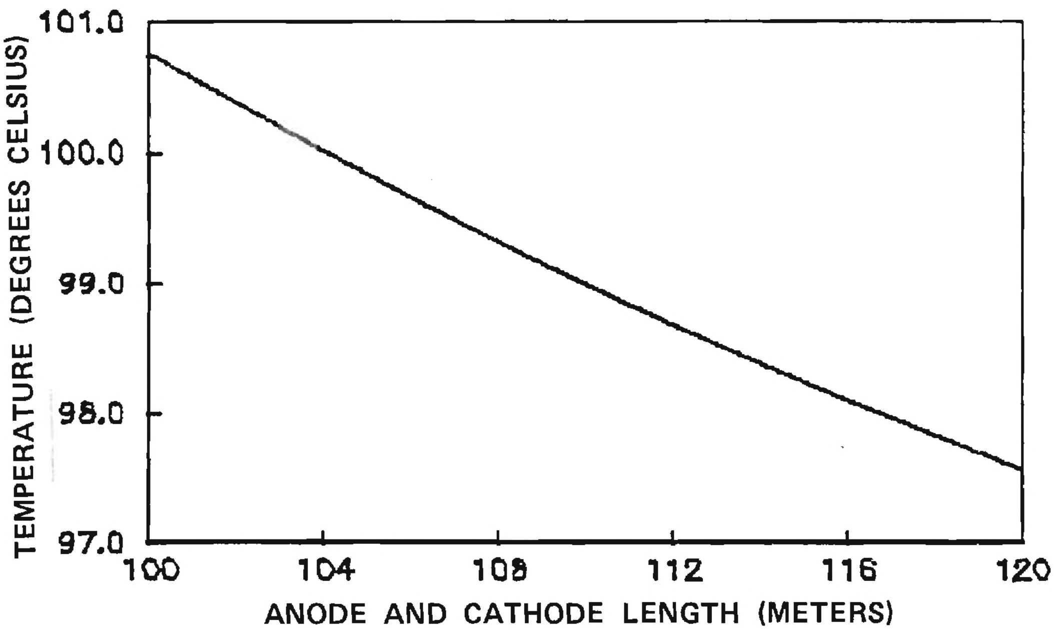


Figure 3. Electrode Temperature Versus Electrode Lengths

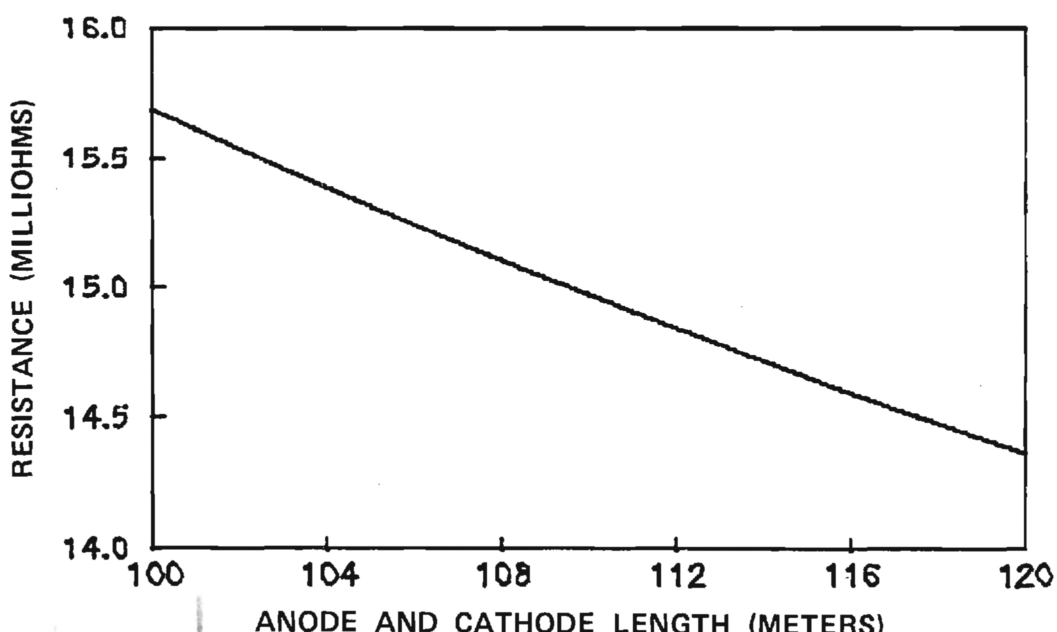


Figure 4. System Resistance Versus Electrode Lengths

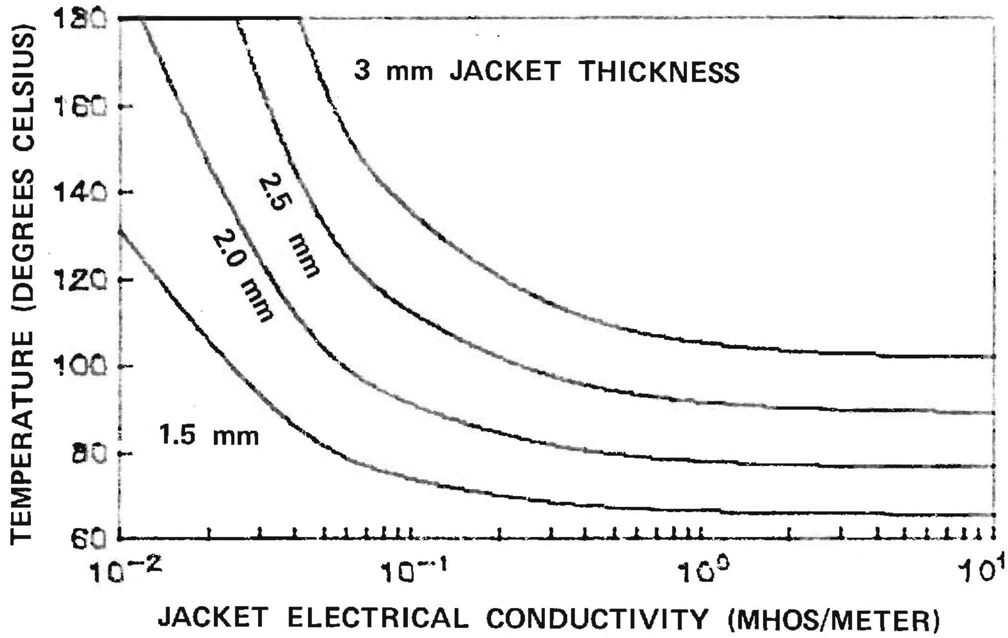


Figure 5. Electrode Temperature Versus Electrode Jacket Electrical Conductivity

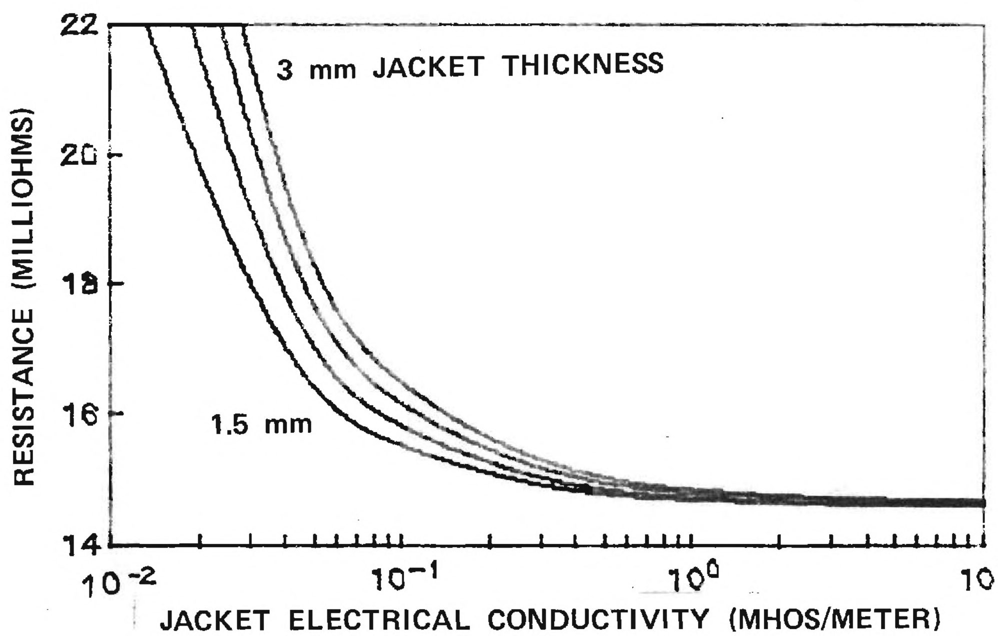


Figure 6. System Resistance Versus Electrode Jacket Electrical Conductivity

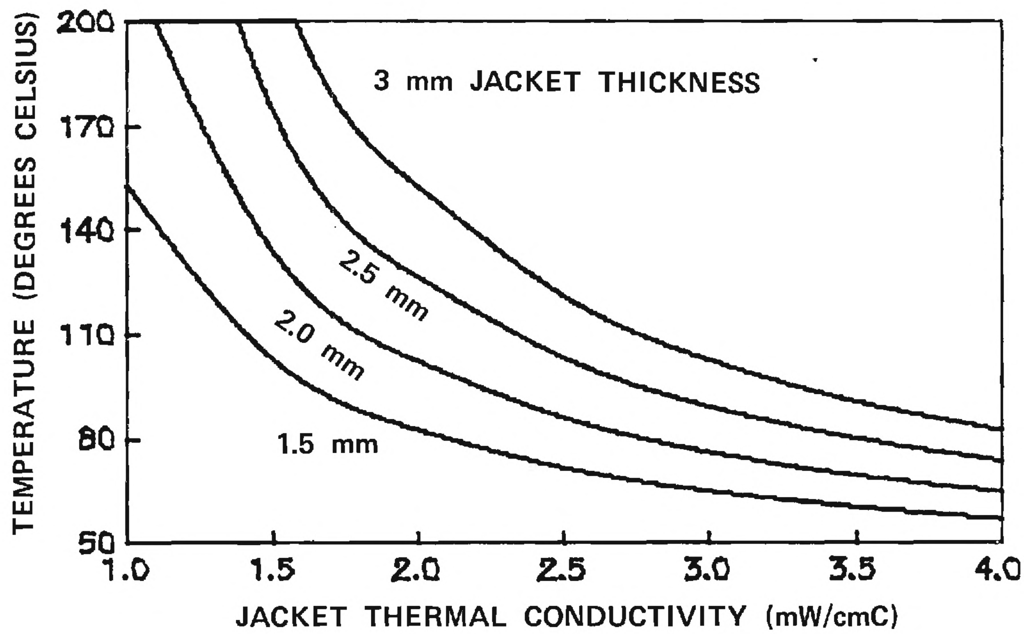


Figure 7. Electrode Temperature Versus Electrode Jacket Thermal Conductivity

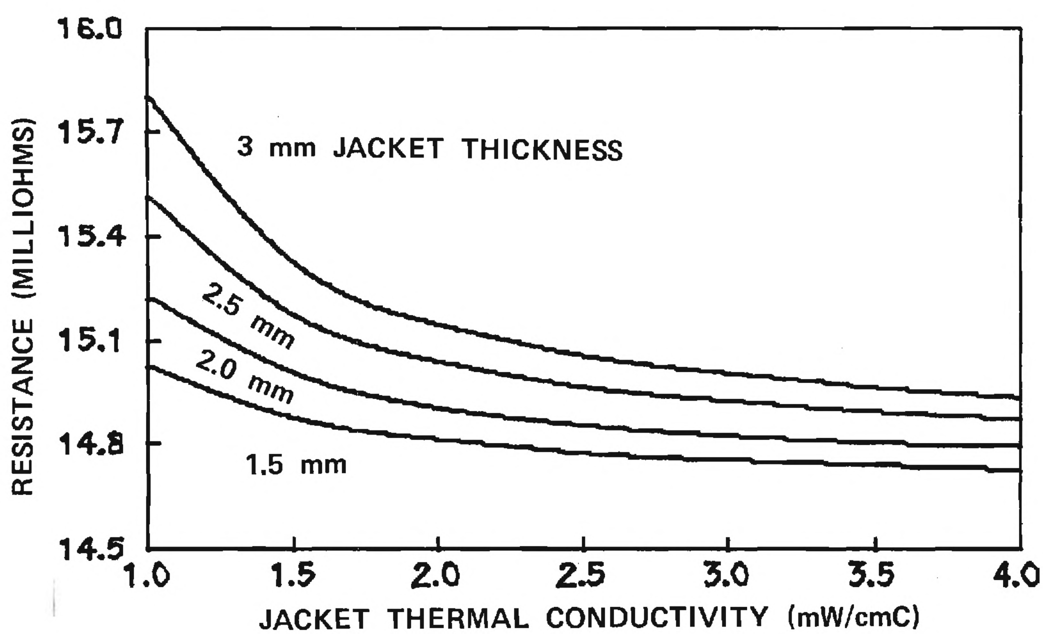


Figure 8. Electrode Temperature Versus Electrode Jacket Thermal Conductivity

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Transient heat flow analysis will continue, culminating in an efficient, accurate computer model for the transient heat flow from minesweeping system S-cables, anodes and cathodes.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date: $ 4,882

This Two Month Period: $ 3,156

Funds Remaining: $ 33,137

Percent of Funds Expended: 12.8%

Percent of Task Completed: 12.8%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrodes

Task Leader: Dr. Robert F. Hochman

Institution: Metallurgy Program
School of Chemical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

Previous studies have shown that basically 20% of the high conductivity graphite (Ketjenblack) has produced the optimum combination of electrical conduction and mechanical properties in Hytrel. Higher compositions of KJB began to show the effects of less abrasion resistance, higher stiffness, and embrittling effects. Therefore initial studies involving the stabilization of the thermal plastic polyester, "hytrel" are being conducted in the 15-20% range of the high conductivity graphite concentration. Later tests will go up to 25% just to verify the possibilities of improved properties in the higher conductivity range maybe realized as a result of the effect of the stabilizer.

The hydrolytic stabilizer for hytrel referred to is a material which has an effective range from 1-5% as per the literature. The optimum concentration has been reported as 2%. Thus the initial range to be studied will be from 1 to 4% of hydrolytic stabilizer.

Table 1 provides the grouping of the basic study materials which are being prepared for study at this time. The properties being evaluated are electrical conductivity, thermal characteristics, mechanical properties and electrical-chemical life. The basic chart is based on the electrical-chemical life, which is the paramount or first consideration for any new material prepared for this application.

Mechanical tensile tests will also be performed on these various combinations. The mechanical properties can be plotted versus percent stabilizer for the various carbon content and the mechanical properties can also be plotted versus the high conductivity carbon for a fixed stabilizer concentration. Additional plots and cross references may be developed with regard to life and other mechanical and physical properties. In the long run a combination of the optimization of all properties and the choice of the best combination of properties for the intended application should be possible once this has been developed.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Continuation of compound stabilized polymer-KJB samples in testing on conductivity and electrochemical developments.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date:	$13,500
This Two Month Period:	$13,500
Funds Remaining:	$68,337
Percent of Funds Expended:	16.5%
Percent of Task Completed:	16.5%

% KJB GRAPHITE	0%	1%	2%	3%	4%
* 20%	Good Mech. Properties Very good conductivity Life: 7-10 hrs.**		Good Mech. Properties Very good conductivity Life: 70-100 hrs.**		
17.5%	Good Mech. Properties Good conductivity Life: Approx. 4-8 hrs**				
15%	Very good mech properties fair conductivity Life: Approx. 4-8 hrs.**				

% STABILIZER

Table 1 - Evaluation program for stablized KJB-Hytrel conductive polymer

*Higher percentages of KJB may be evaluated if the improvement in mechancial properties as a results of the stablizer indicates a potential for an improved material with 20+% KJB.

** Life is based on effective electrochemical operation at the highest current densities.

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

A high current minesweeping electrode system including an S-cable, Anode and Cathode have been computer modeled and verified using previously obtained data. The computer model is being upgraded to include transient heating. Transient heating will occur either when the electrode current is pulsed or when the cable is moved slowly through the water. The later problem is more difficult as the heat flow analysis includes convection as well as conduction. A new parameter called thalpence must be determined for the analysis of the convective heat flow. Progress has been made on the transient heat flow and several working models have been developed. The most accurate models however require a lot of computer time and require determination of approximately 300 eigenvalues to the Bessel heat flow equation prior to running the program. This two step process and lengthy computation time make this method of analysis bulky in carrying out parametric evaluations of the electrode system. Work is now underway to approximate the heat flow equation by a finite difference equation and solve it digitally.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

The transient heat flow analysis will continue, culminating in an efficient, accurate computer model for the transient heat flow from minesweeping system S-cables, anodes and cathodes.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date:	$ 1,725.63
This Two Month Period:	1,725.63
Funds Remaining:	36,293.37
Percent of Funds Expended:	4.5%
Percent of Task Completed:	4.5%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 **Title:** Conductive Polymer Development for Minesweeping Electrodes

Task Leader: Dr. Robert F. Hochman

Institution: Metallurgy Program
School of Chemical Engineering
Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

See attached sheets

The major work of the program to date has been:

A. Developing sound, effective compounding techniques to prepare reproduceable samples of the various hytel-KJB-stablizer compositions.

B. Design and develop equipment for electrochemical measurements of life of the materials produced by effective compounding techniques.

C. Develop a system for effective measurements, within 5-10% accuracy, the thermal conductivity of the various compositions.

The tests for both electrical conductivity and mechanical properties are also being run on samples after they are prepared. However, the techniques of these tests are more defined, and the sample preparation and the ability to obtain and reproduce results have not required development of new or sophisticated techniques or modification of equipment as has been needed in the three aforementioned studies.

Techniques and equipment have been advanced to the point were several characteristics of the KJB upon the hytrel, the effect of the hytrel stabilizer, or a combination of the two. Figure 1 is a chart of the samples that are being studied and are planned for studing. Choice of composition is based on a comprehensive evaluation of preliminary data that has been obtained to date. Attached to Figure 1 is a summary of the generalized information of each composition.

It must be remembered that a major portion of the work to date has been in the development and refinement of techniques on equipment to get to a stage in the project where reproducible quantities of materials could be made. It appears that at this time extensive data, from multiple samples will be possible through the judicial development of the various equipment and experimental techniques.

Data on thermal conductivity has also been developed. Completion of both the system and techniques has been time consuming and tedious, but now realistic data is being obtained. To establish the credibility of our system, thermal data conductivity measurements were taken on as-received; compounded hytrel polymer. The average thermal conductivity was found to be 5.66×10^{-4} calories per centimer, second degree %. The data on the pure samples is provided in Table 2 and is within 5% reproducibility from sample to sample. This data however is about 20% lower than the conductivity reported in the literature, however, because of the sensitivity of thermal measurements in low conductivity material variations from batch to batch is normal. Additional studies have been made on our basic sample of 2% stabilized-hytrel with 20% KJB. Data for these tests are shown in Table 3. This data indicates that the basic compounded 20-2, which has been shown to be a useful material in electrochemical life has a thermal conductivity approximately 45% better than the literature value we've used previously. This is going to provide a major improvement in the development of electrical designs because of the excellent ability to remove heat from the system.

PERCENT STABLIZER

Percent KJB Graphite	1	2	3	4	5	6
22.5		P_4		P_3		6 Lab Sample Testing Completed 6-1-81
20		1 *Lab Samples **Commerical Sample *Testing completed **In process - completion approx. 7-1-81	P_1	2 *Lab Samples **Commerical Sample *5-1-81 **7-1-81	P_2	7 Lab Sample Testing Completed 6-1-81
17.5		3 Lab Sample Testing completed 6-1-81		4 Lab Sample Testing completed 5-1-81		
15		5 Lab Sample Testing completed ≈ 4-1-81				

Samples 1, 2, 3 etc. in order of priority

P - Potential samples in order of present priority

Figure 1. Chart of Compound Compositions under Study and Proposed.

Sample 20-2

Based on the original studies that showed 20% KJB-Hytrel as an optimum in properties for the system in the unstablized condition.

Electrical conductivity - very good, 10 to 20 ohm resistivity for typical samples.
Mechanical properties - very good to excellent - includes flexibility, wear, and abrasion resistance, etc.
Electrochemical stability - 70 hrs. at maximum current density and 200 hours at 5700 amps.
Thermal conductivity - good accurate tests are in progress.

Notes:

a) Some marked base of electrical on mechanical properties with long electrochemical exposure.
b) These properties can be required to some extent by mechanical removal of surface deterioration layer.
c) Commerical batchs of approximate 10 lbs. are now in progress. This should indicate manufacturing reliability and properties more representative of the potential commerical material.

Sample 20-4

Based on the fact that the stablizer promotes electrochemical stability. This system should have higher mechanical values and possibly improved electrical and electrochemical properties.

Material is in lab fabrication studies at present.

Sample 17.5-2

Based on potential for lower carbon for better overall mechanical properties and improved mixing to give good electrical conductivity. Lab samples have been prepared.

Electrical conductivity - fair, tests to date indicate significantly lower results than 20-2 or 20-4.
Mechanical properties - excellent wear and abrasion resistance, and excellent flexibility.
Eletrochemical properties - under study.

Sample 17.5-4

Based on the consideration that increased stabilizer will improve both mechanical and electrochemical properties. In lab tests at present.

Sample 15-2

Based on lower carbon for better over all mechanical properties. The mechanical properties are excellent but electrical resistance is running more than a magnitude higher than 20-2 materials, because of this poorer electrochemical properties plus thermal problems are indicated. Further testing has been abandonded.

Sample 15-4

Abandoned for the same reasons as 15-2.

Sample 22.5-6

Designed to test the limits of the stabilizer and new techniques to increase carbon mixing. This sample is designed to test for improved electrical properties while trying to maintain an optimum in mechanical properties. Samples are in lab preparation studies. The potential of 22.5-2 and a 22.5-4 samples are also being examined in these mixing studies.

Potential Samples

Samples designated as such may be prepared if a particular improvement is indicated by tests of other samples presently under study.

Table 2

Plane Hytrel

No. of Run	Thermoconductivity k
1	$5.72 \times 10^{-4} \frac{\text{cal}}{\text{cm sec deg}}$
2	$5.60 \times 10^{-4} \frac{\text{cal}}{\text{cm sec deg}}$
Average $\bar{k}$	$5.66 \times 10^{-4} \frac{\text{cal}}{\text{cm sec deg}}$

Literature value for pure Hytrel

$$k = 6.9 \times 10^{-4} \frac{\text{cal}}{\text{cm sec deg}}$$

Table 3

Hytrel 20-2

No. of Run	Thermoconducitivity, k
1	1.02×10^{-3} cal/cm sec deg
2	9.95×10^{-4} cal/cm sec deg
3	1.02×10^{-3} cal/cm sec deg
Average $\bar{k}$	$1.01 \times 10^{-3} \pm 1\%$ cal/cm sec deg

B. WORK SCHEDULE STATUS

On Schedule

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Continue compounding and thermal conductivity tests. Complete initial runs of 17.5-4, 17.5-2 and 20-4 electrochemical life tests.

D. PROBLEM AREAS

Most problems in development of test equipment and procedures in compounding and thermal conductivity are clearing up.

E. FUNDS EXPENDED

To Date:	$41,000
This Two Month Period:	$13,200
Funds Remaining:	$40,837
Percent of Funds Expended:	51%
Percent of Task Completed:	51%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

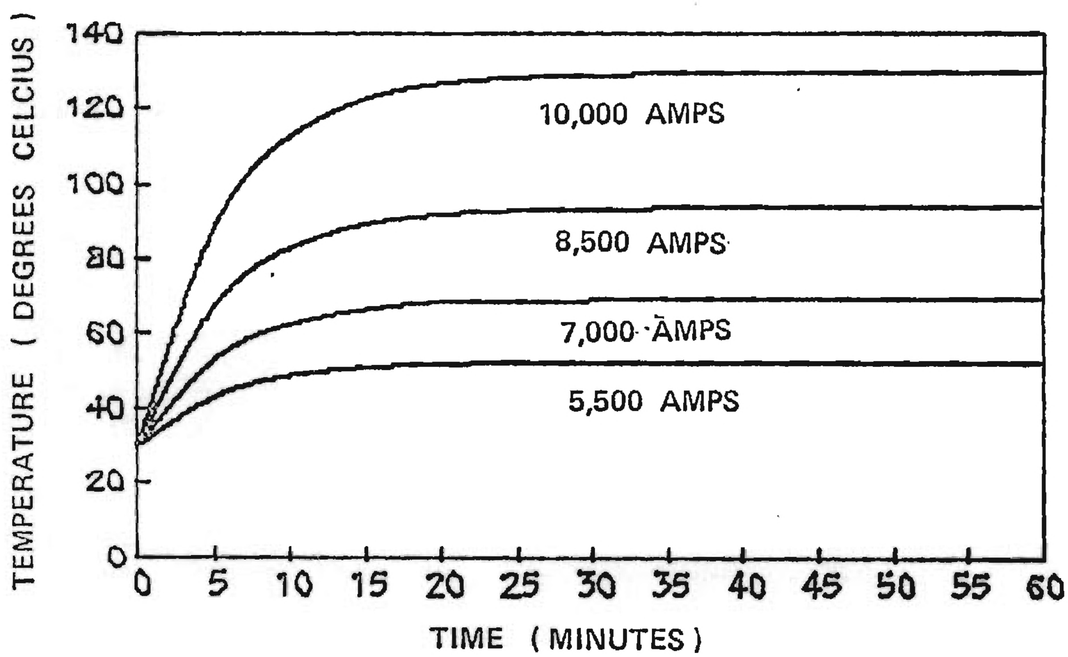
Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

The transient thermal analysis computer program is now operational. Figure 1 shows first results. This figure shows the temperature of the inner aluminum layer of the electrodes versus time since application of minesweeping current. The electrodes used in this analysis are the same as described in the previous report. Four current levels are shown. This figure suggests that large current levels can be used for short pulses (pulses of duration less than 5 minutes, depending on current level) without exceeding 100 degrees celsius. However, the time average current must still be equal to or less than the design current. The above conclusions are based solely on thermal considerations. Electrochemical considerations will possibly shows that the lifetime of an electrode may be greatly shortened by large current pulses as this increases current denstiy and accelerates jacket deterioration.

FIGURE 1



ELECTRODE CONDUCTOR TEMPERATURE VS. TIME

FOR DIFFERENT SWEEP CURRENTS

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Measured material thermal conductivities and electrochemical resistances will be used in the computer analysis program to see the effect on system performance of the new materials.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date: 11,859

This Two Month Period: 6,587

Funds Remaining: 26,160

Percent of Funds Expended: 31%

Percent of Task Completed: 31%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report April-May 1981

Order Number: HR- 22 **Title:** Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

See Attached.

ATTACHMENT

Computer simulation of the use of higher thermal conductivity conducting Polymer jacket material has been completed. It is shown that reduced electrode diameters are possible using the more thermally conductive material but longer electrode lengths are necessary. Table I and Figure 1 show the electrode parameter values and radial current densities along the anode and cathode electrodes respectively using standard Hytrcal jacket material with thermal conductivity of 2.8×10^{-3} W/cm C°. The diameter of the electrodes is 10.5 cm, length of each electrode is 110 m and the total aluminum cross section is 3.3 million circular mils. Table II and Figure 2 show the electrode parameter values and radial current densities respectively using the experimental high thermal conductivity jacket material. This material has a thermal conductivity of 4.23×10^{-3} W/cm C°, an increase of 51%. The electrodes have been reconfigured to keep the temperature below 100°C at operating current. The diameter was reduced 9.12% to 9.23 cm and the total amount of aluminum conductor was reduced by 24.2% to 2.5 million circular mils. The length of the electrodes increased, however, 7.3% to 118 m to keep the total system resistance under 15 milliohms.

B. WORK SCHEDULE STATUS

Work is on schedule

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Work will begin on analysis and design of non-bouyant test section.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date: $18,622

This Two Month Period: 6,763

Funds Remaining: 19,397

Percent of Funds Expended: 51%

Percent of Task Completed: 51%

TABLE I. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	10.500 cm (4.134 inches)
Length	110 meters (360.9 ft)
Maximum Current	8500 amperes
Maximum Temperature	100.0^{o}C
Maximum System Resistance	15.0 milliohm
Bending Radius	3 feet
Stiffness	7.52 x 10^{4} lb/in^{2}
Core	
Material(s)	Heat resistance ABS and Silicon Foam
Diameter	8.244 cm (3.246 inches)
Thermal Conductivity	7.53 x 10^{-4} W/cm^{o}C
Electrical Conductivity	0.0 mho/m
Specific Gravity	0.3
Core Sheath	
Material	4" Mylar Tape 2 mills thick with 45 overlap
Thickness	3.8 mills
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	0.0 mho/m
Specific Gravity	1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	2.36 W/cm^{o}C
Electrical Conductivity	3.536 x 10^{7} mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	56
Winding Pitch Angle	22^{o}
Shape of Conductors	Round
Size of Conductors	29,464 CM
Percent Fill of Aluminum	75.0
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 2 mills thick with 45% overla
Thickness	3.8 mills
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	.5 mho/m
Specific Gravity	1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	2.36 W/cm°C
Electrical Conductivity	3.536×10^{7} mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	67
Winding Pitch Angle	21.9
Shape of Conductors	Round
Size of Conductors	24,627 CM
Percent Fill of Aluminum	74.6
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	2.8×10^{-3} W/cm°C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30°C
Thermal Conductivity	5.796×10^{-3} W/cm°C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

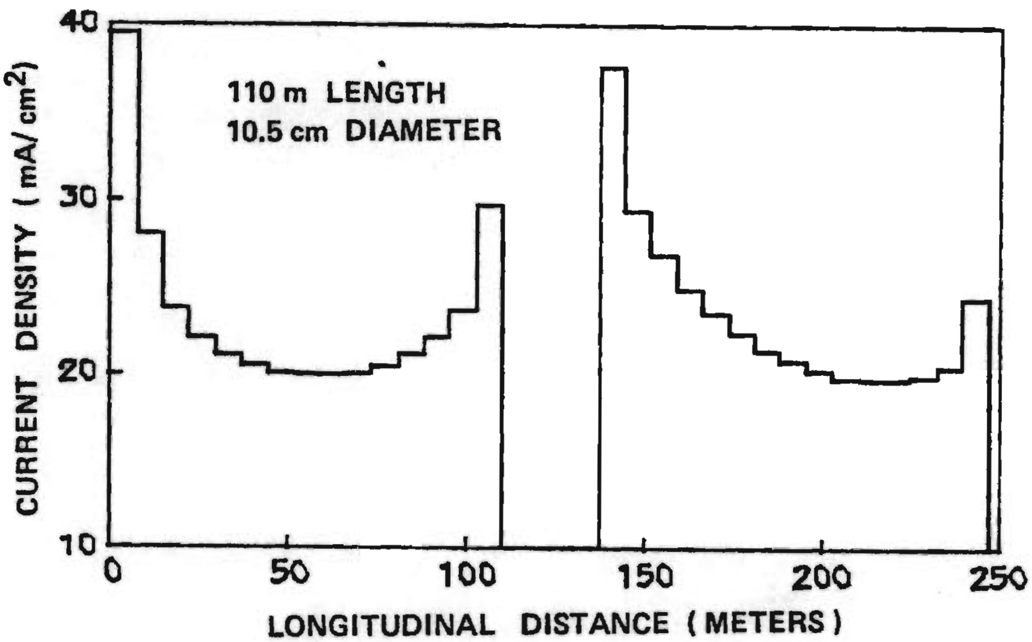


FIGURE 1. ANODE & CATHODE RADIAL CURRENT DENSITIES VS. LONGITUDINAL DISTANCE

TABLE II. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	9.230 cm (3.634 inches)
Length	118 meters (360.9 ft)
Maximum Current	8500 amperes
Maximum Temperature	100.0°C
Maximum System Resistance	15.0 milliohm
Bending Radius	3 feet
Stiffness	4.48×10^4 lb/in^2
Core	
Material(s)	Heat resistance ABS and Silicon Foam
Diameter	7.201 cm (2.835 inches)
Thermal Conductivity	7.53×10^{-4} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	0.3
Core Sheath	
Material	4" Mylar Tape 2 mills thick with 45 overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	2.36 W/cm°C
Electrical Conductivity	3.536×10^7 mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	57
Winding Pitch Angle	21.2°
Shape of Conductors	Round
Size of Conductors	21,930 CM
Percent Fill of Aluminum	75.4
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	.5 mho/m
Specific Gravity	1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	2.36 W/cm$^{\circ}$C
Electrical Conductivity	3.536 x 10^{7} mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	68
Winding Pitch Angle	21.4°
Shape of Conductors	Round
Size of Conductors	18,382 CM
Percent Fill of Aluminum	75.1
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95 x 10^{-3} W/cm$^{\circ}$C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95 x 10^{-3} W/cm$^{\circ}$C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	4.23 x 10^{-3} W/cm$^{\circ}$C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30°C
Thermal Conductivity	5.796 x 10^{-3} W/cm$^{\circ}$C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

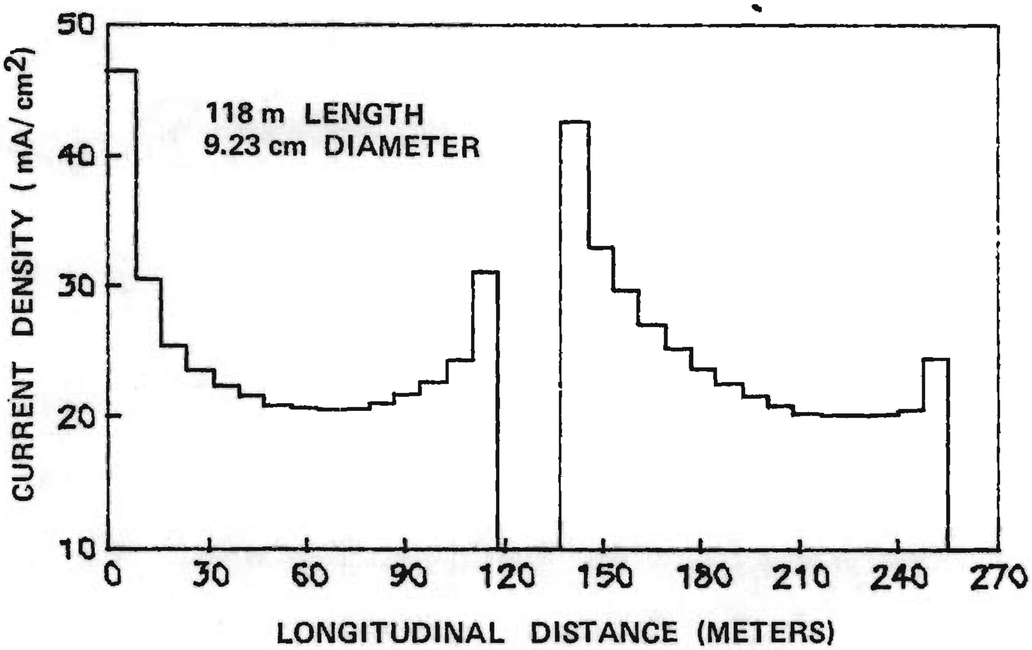


FIGURE 2. ANODE & CATHODE RADIAL CURRENT DENSITIES VS. LONGITUDINAL DISTANCE

Monthly Report (MET) on E19-E22

A program has been developed on the CDC 70/74-6400 computer in order to evaluate the thermal conductivity from empirical data. Results from five different experiments will be analyzed in a single job and a linear regression of least square analysis has been assumed. The output is to be plotted to the VERSATEC electrostatic plotter.

A new sample of plane Hytrel has been pressed for investigation, an average conductivity value of 5.700×10^{-4} cal./cm./sec./deg. was obtained which deviates from the latest value by only 0.7%. The implication of this result is that our experimental results are sufficient and dependable for an optimization study. Stabilizer appears to have significant effect on the thermal conductivity. A 20% lower in conductivity was obtained for Hytrel with a 15% KJB and 2% MX-10. More experiments as yet need to be done in order to verify this effect. The basic compounded Hytrel 20-2, which has been shown to be a useful material in electrochemical life, has a thermal conductivity approximately 45% better than the literature value we have used previously and the result is within a 10% of reproducibility to the latest result. A 17.5-2 Hytrel sample was reported to about 13% lower in conductivity to the 20% KJB Hytrel. More experiments are planned for further verification of the above results.

Table I through V provide data on pure Hytrel plus 15, 15-2, 20-2 and 17.5-2 mixtures of KJB and stabilizer. Figure I-V are curves showing the reproducibility of the results. The large increase in thermal conductivity provides some helpful alterative in design of a first electrode system.

Preliminary data on resistivity and electrochemical life at 36 mA/cm^2, is shown in Table VI. Additional data to clarify these results is underway and more uniform samples are being compounded for future studies.

TABLE 1 Thermal Conductivity for ~~Plane~~ Plain Hytrel

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY, k (cal/cm/sec/deg)
1	5.545×10^{-4}
2	5.722×10^{-4}
3	5.792×10^{-4}
4	5.785×10^{-4}
5	5.598×10^{-4}
AVERAGE	5.700×10^{-4}

TABLE II Thermal Conductivity for Hytrel with 15% KJB

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY, K (cal/cm/sec/deg)
1	1.221×10^{-3}
2	1.152×10^{-3}
3	1.179×10^{-3}
AVERAGE	1.183×10^{-3}

TABLE III. Thermal Conductivity for 15% KJB Hytrel with 2% MX-10

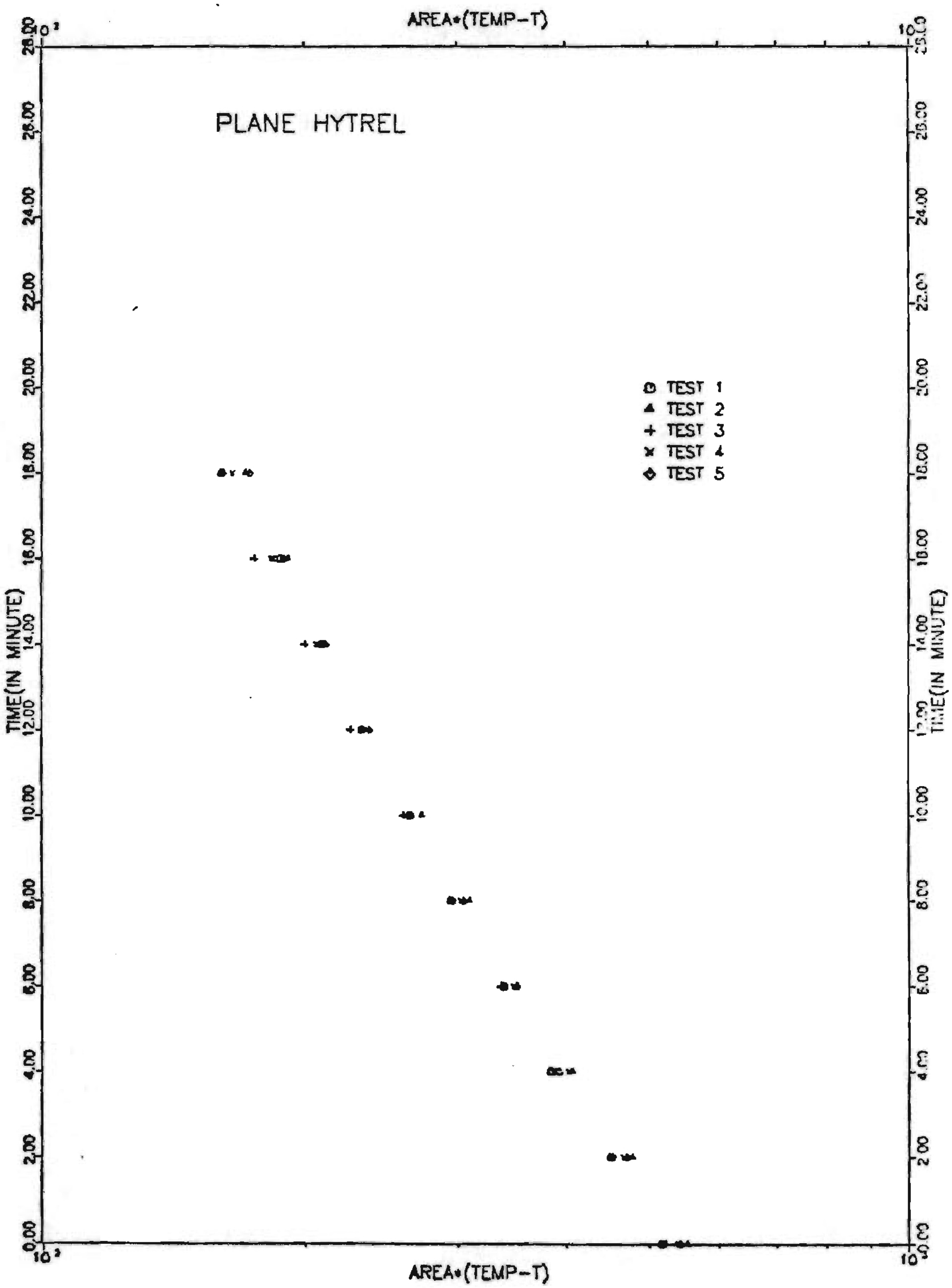
EXPERIMENT (NO.)	THERMAL CONDUCTIVITY, k (cal/cm/sec/deg)
1	1.018×10^{-3}
2	1.023×10^{-3}
3	9.356×10^{-4}
4	9.056×10^{-4}
5	9.112×10^{-4}
AVERAGE	9.586×10^{-4}

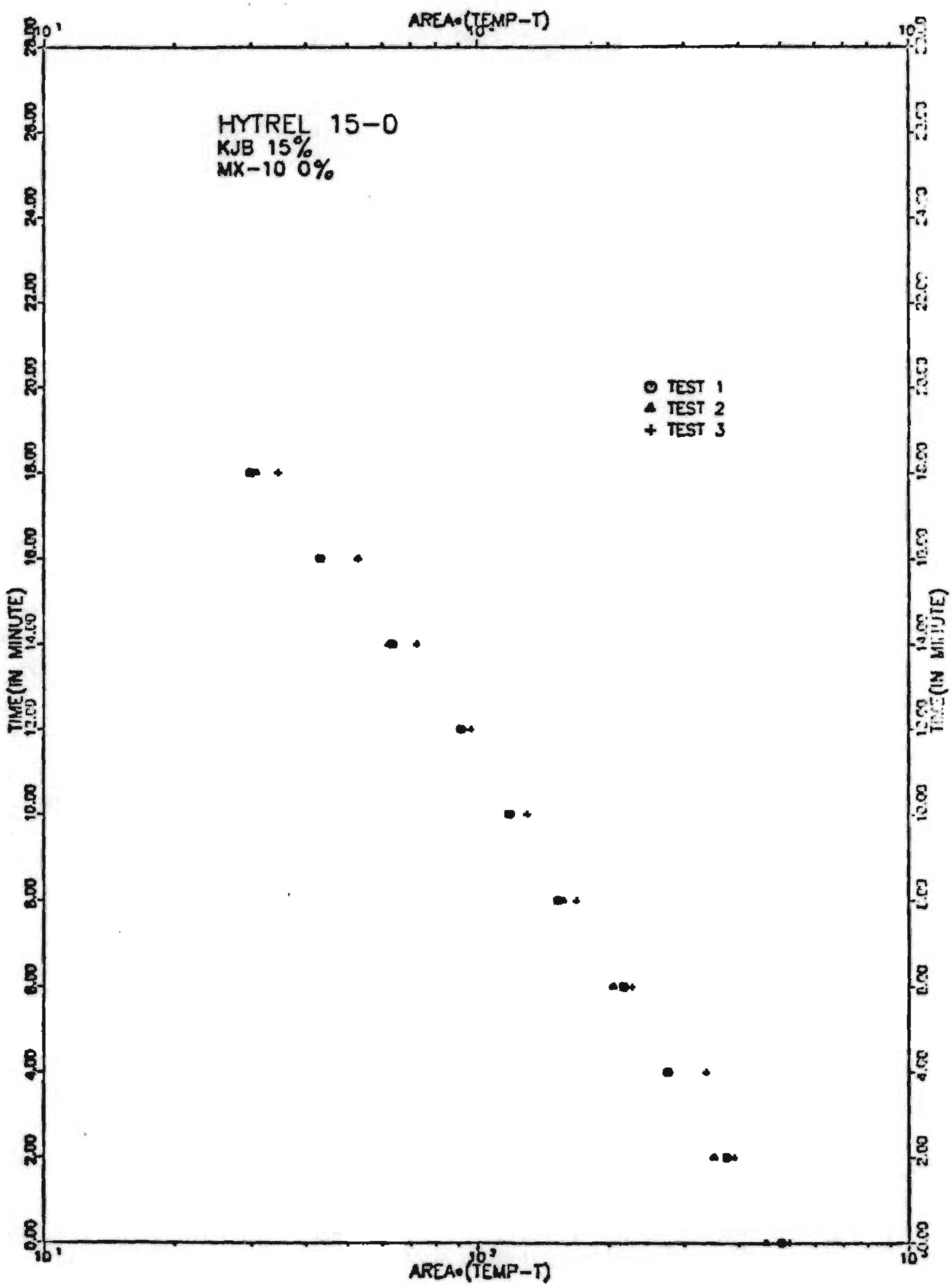
TABLE IV Thermal Conductivity for 20%KJB Hytrel with 2% MX-10

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY, k (cal/cm/sec/deg)
1	1.020×10^{-3}
2	8.772×10^{-4}
3	1.020×10^{-3}
4	8.418×10^{-4}
5	8.309×10^{-4}
AVERAGE	9.180×10^{-4}

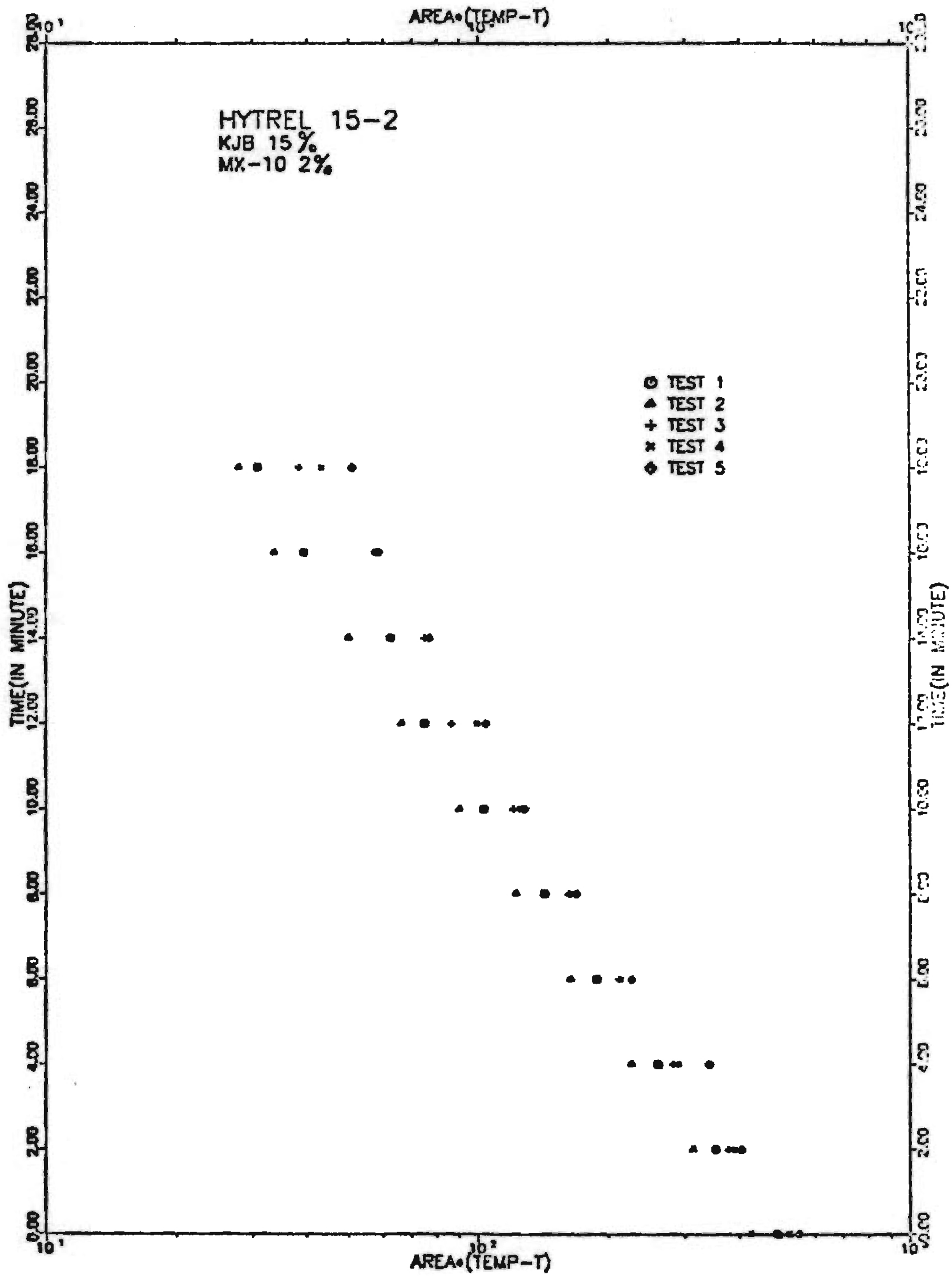
TABLE V Thermal Conductiyity for 17.5% Hytrel with 2% MX-10

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY, k (cal/cm/sec/deg)
1	$8.624X10^{-4}$
2	$7.652X10^{-4}$
AVERAGE	$8.138X10^{-4}$

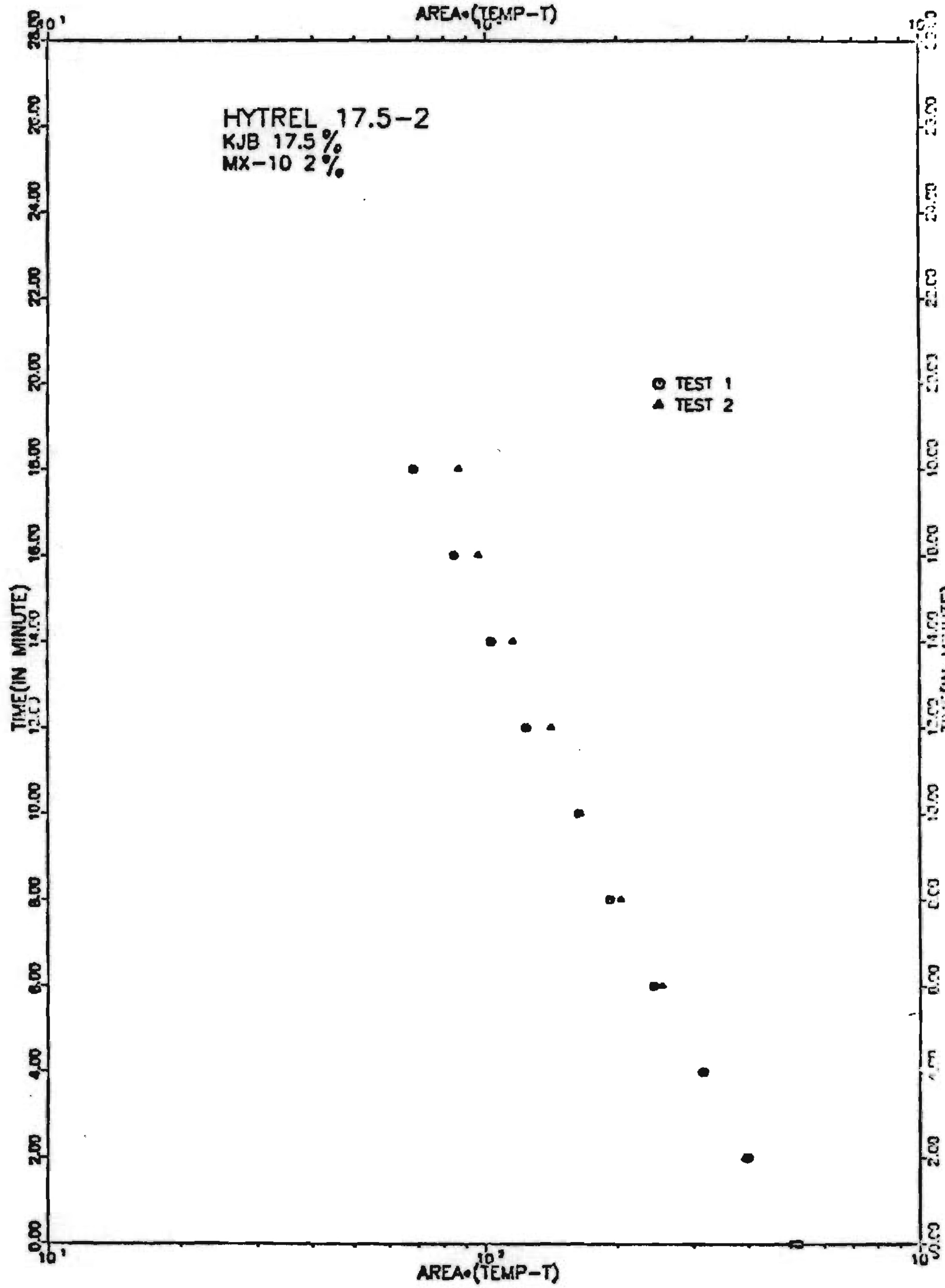

AREA*(TEMP−T)
PLANE HYTREL
TEST 1
TEST 2
TEST 3
TEST 4
TEST 5
TIME(IN MINUTE)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
26.00
28.00
AREA*(TEMP−T)

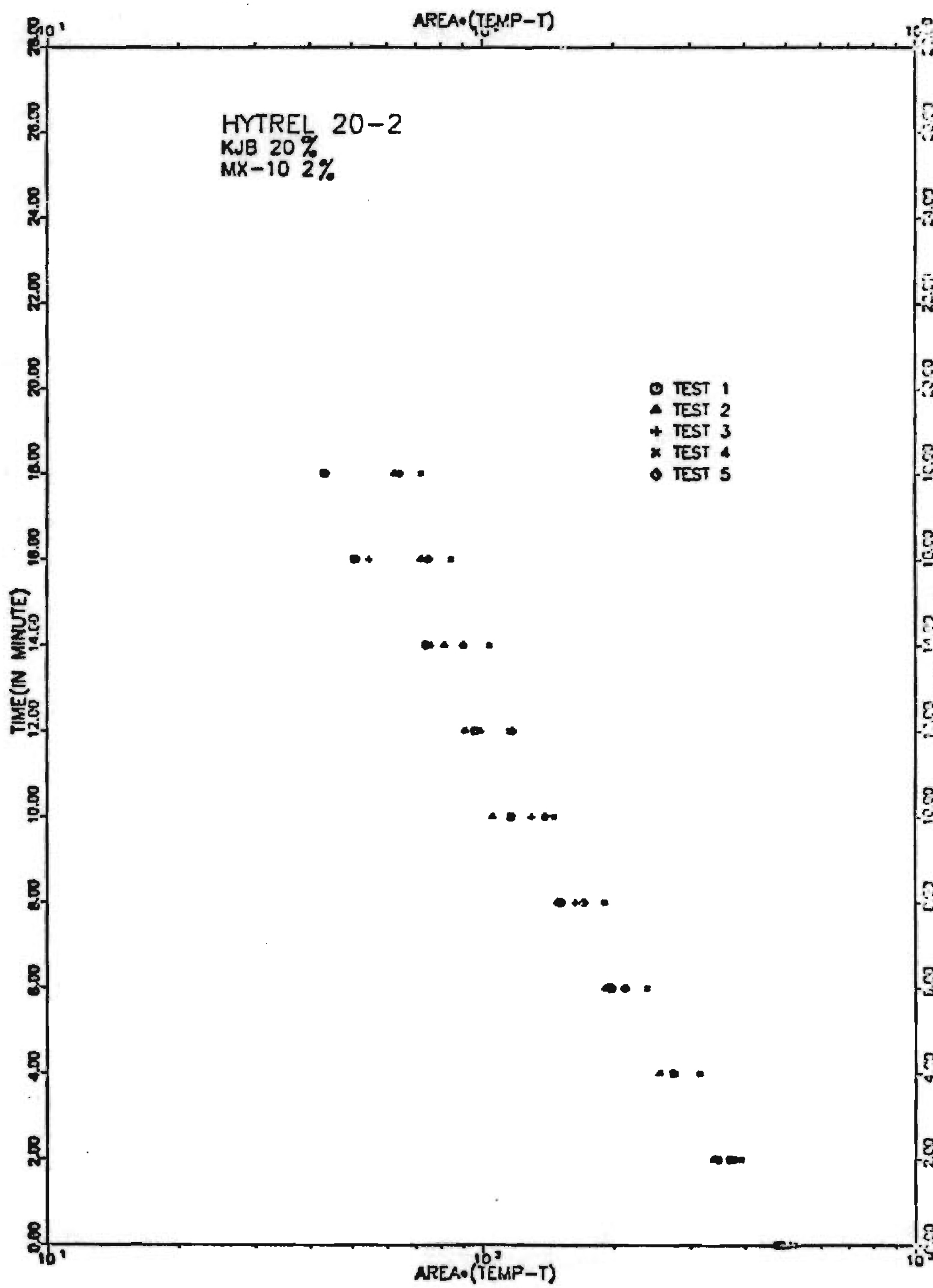


AREA*(TEMP-T)
HYTREL 15-0
KJB 15%
MX-10 0%
TEST 1
TEST 2
TEST 3
TIME(IN MINUTE)



AREA•(TEMP-T)
HYTREL 15-2
KJB 15%
MX-10 2%
TEST 1
TEST 2
TEST 3
TEST 4
TEST 5
TIME(IN MINUTE)


AREA*(TEMP-T)
HYTREL 17.5-2
KJB 17.5 %
MX-10 2 %
TEST 1
TEST 2
TIME(IN MINUTE)
AREA*(TEMP-T)



AREA•(TEMP-T)
HYTREL 20-2
KJB 20%
MX-10 2%
TEST 1
TEST 2
TEST 3
TEST 4
TEST 5
TIME(IN MINUTE)
AREA•(TEMP-T)

Table VI Hytrel - KJB - Stabilizer Samples

KJB - Stab.	Resistivity	Life ($36\ mA/cm^2$)
17.5-2	50 Ω·cm	8.5 hrs
20-2	37 Ωcm	24 hrs
20-4	37 Ωcm	16.5 hrs
22.5-2	2 Ωcm	18 hrs

Corrosion tests in stirred ASTM ocean water @ 25°C
current density $36\ mA/cm^2$
clamped, compressive stress 130 psi

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report 1 August 1981

Order Number: HR-22 **Title:** Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

Many computer simulations of the performance of the new jacket materials have been conducted to assess the effects of improved thermal and electrical conductivities.

Development of the computer program for the non-bouyant test section continues.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

1. Computer analysis of effect of measured electrochemical resistances.
2. Finish computer code for non-bouyant test section.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date: $22,083.00

This Two Month Period: $6,828.00

Funds Remaining: $15,936

Percent of Funds Expended: 58%

Percent of Task Completed: 58%

E-21-E22/
E-19-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report

Order Number: HR- 22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: R. F. Hochman

Institution: Georgia Tech·

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

Overall test results; thermal conductivity, electrical conductivity and mechanical strength, indicate the best range of materials which can be reproducibly proposed consist of the compositions listed in table I below.

Hytrel	%KJB	%Stablizer
Bal.	20	1
Bal.	21	1
Bal.	22	1
Bal.	20	2
Bal.	21	2
Bal.	22	2

Table I. Best Potential Conductive Polymer Compositions

Preliminary tests of electrochemical life has shown samples in this composition range to have 16 to 26 hours life at 180% of the average current density of the proposed electrode. At the average current density 30 to 40 hours life is easily obtainable. In depth data is now being compiled on all electrochemical life measurements.

B. WORK SCHEDULE STATUS

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

An initial attempt will be made on 8-6-81 to extrude a tube of 20-2 and 22-2 for actual large scale test measurements.

D. PROBLEM AREAS

No problems

E. FUNDS EXPENDED

To Date: $70,411

This Two Month Period: $8,880

Funds Remaining: $11,426

Percent of Funds Expended: 85%

Percent of Task Completed: 85%

E21-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report 1 October 1981

Order Number: HR- 22 **Title:** Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

Computer simulations have been carried out to compare electrodes which use the new jacket materials to bare aluminum electrodes. The benefits of lower drag, improved handlelability, lower maintenance and longer life are somewhat offset by a 10% increase in electrode length.

The computer code for analysis of the non-bouyant test section has been completed.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Write final report.

D. PROBLEM AREAS

None

E. FUNDS EXPENDED

To Date: $28,005

This Two Month Period: $5,922

Funds Remaining: $10,014

Percent of Funds Expended: 74%

Percent of Task Completed: 74%

E-21-E22/
E-19-E22

BIMONTHLY STATUS REPORT

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Period Covered: 1 October 1981 - 30 November 1981

Order Number: HR-22 Title: Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. Edward B. Joy

Institution: School of Electrical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

The new anode and cathode electrochemical resistance equations for the new conducting polymer electrode materials have been computer implemented. Simulations show almost no effect on electrode temperature but show an almost 10% increase in system resistance.

B. WORK SCHEDULE STATUS

Work is on schedule.

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Write final report.

D. PROBLEM AREAS

None.

E. FUNDS EXPENDED

To Date: $37,809

This Two Month Period: $9,804

Funds Remaining: $210

Percent of Funds Expended: 99%

Percent of Task Completed: 99%

E21-E22

NAVAL COASTAL SYSTEMS CENTER
OMNIBUS R&D PROGRAM
CONTRACT NO. N00612-79-C-8004

Bimonthly Status Report (to 11/20/81)

Order Number: HR- 22 **Title:** Conductive Polymer Development for Minesweeping Electrode Jackets

Task Leader: Dr. R. F. Hochman

Institution: Metallurgy Program, School of Chemical Engineering, Georgia Institute of Technology

A. SUMMARY STATEMENT OF WORK COMPLETED DURING THE PAST TWO MONTHS

See attached.

B. WORK SCHEDULE STATUS

Work is on schedule

C. BRIEF STATEMENT OF PLANNED WORK FOR THE NEXT TWO MONTHS

Completion of Final Report

D. PROBLEM AREAS

Maintaining properties of conductive polymer in manufacturing conditions.

E. FUNDS EXPENDED

To Date: $80,500

This Two Month Period: -

Funds Remaining: $837

Percent of Funds Expended: 99%

Percent of Task Completed: 99%

ATTACHMENT

The principal data and information to be covered in this report will be the data on two sets of electrochemical tests on extruded conductive polymer and information on developments to circumvent some of the manufacturing difficulties that have arisen in these conductive polymers when prepared by industrial techniques.

It is important to remember in the evaluation of the polymers two things are different in these particular polymers than in the previous studies that showed lives in excess of 50 hours (one result as high as 70 hrs.) at 20 $\frac{mA}{cm^2}$. Differences in the fabrication techniques due to use of industrial equipment resulted in stabilizer being lost due to heating above the satisfactory or good fabrication temperature range for hytrel and the ioms stabilizer. In addition some carbonization of the hytrel was also occurring. Add to this that the electrochemical tests were also done in a slightly different manner, in that the specimens were put under a load to better simulate potential loading effects upon the material, and indeed this may be more stringent than we should be in our electrochemical testing. The true results will only be well defined when we finally test the three tubular type sections we are preparing for NCSC.

ELECTROCHEMICAL LIFE IN ANODIC POLARIZATION STUDIES

The electrochemical life was determined by using two constant current density tests at 20 $\frac{mA}{cm^2}$ and 36 $\frac{mA}{cm^2}$ and these are shown in Tables 1 and 2 and are summarized in Figure 1. Figure 1 also provides information with regard to the types of samples that were tested and the relative amount of carbon and stabilizer used in each sample. At this time the mechanism of deterioration of the carbon filled polymer is not precisely known although one facet of the problem we do know, that is oxidation of the carbon to carbon dioxide plus the potential for formation of carbonates. It appears that loss of stabilizer due to the slightly excessive heating in commercial type processing has resulted in a decrease in electrochemical life. The stabilizer generally slows the reaction with moisture. Data on variations in potential and current for some of the shorter lived materials also indicated that some non-uniformity of mixing in can occur to some extent in commercial processing compared to hand processing in the lab.

A second series of corrosion tests consisted of anodic polarization. Anodic polarization curves showed variations. This appears to be mainly due to non-uniformity of samples and to some defects in the conductive polymer prepared commercially. This all points to the importance of a much better control process. Some of the basic data obtained from the anodic polarization studies is given in Tables 3 and 4. The latter calculates some of the Tafel slopes from the anodic polarization curves. At present we are evaluating the characteristics of these Tafel slopes with the prospect of using this data in some way to determine the basic electrochemical characteristics of the material to have a quicker and easier evaluation of the potential stability of the material.

EVALUATION OF MATERIAL AND ON-GOING RESEARCH IN POTENTIAL MATERIALS.

The electrochemical results were somewhat sobering after the excellent data that had been obtained for stabilized material, prepared in laboratory quantities, under careful mixing procedures and temperature controls. Thus it is obvious that life, like 70 hours, is possible and maybe even greater life is possible with some changes in fabrication technique. However, it is important to evaluate what can be effectively produced at this time under commercial conditions and to upgrade commercial preparation to the point where it is producing the optimum material.

There are a number of changes we are presently evaluating:

a) A lower viscosity hytrel (DuPont 5526) which would allow lower temperature mixing;

b) Evaluating stabilizers to determine if a higher temperature stabilizer is available;

c) Precast hytrel from a solution with a high carbon density to determine the best properties of such an add mixture. Difficulties have arisen in this study because of the tendency for layering of the carbon, either at the top or the bottom, depending upon the viscosity of the polymer solution which is dependent on drying time. However, it may be possible to achieve the right combination of variables to prepare material in this fashion.

d) We are also looking at the potential for adding some regular graphite to the mixture, not for conductivity, but to improve the lubrication qualities of the material and which will allow extrusions at slightly lower temperatures.

Finally, from all the new materials, polyurethane appears to offer some relief to this problem, both from a higher preparation temperature and a much greater resistance to moisture absorption. Thus the necessity for a stabilizer is not or may not be important for these materials. We have obtained polyurethane rubber and are now preparing samples, both for electrical resistance and hopefully for a couple of electrochemical life tests.

TABLE 1.

($i = 20$ mA/cm^2)

Samples	20-1	20-2	21-1	21-2	22-1	22-2
Current Applied (I, mA)	42	41	47	48	50	42
Electrochemical Life (Hrs)	29	32	27.5	29	32	31

TABLE 2.

($i = 36$ mA/cm^2)

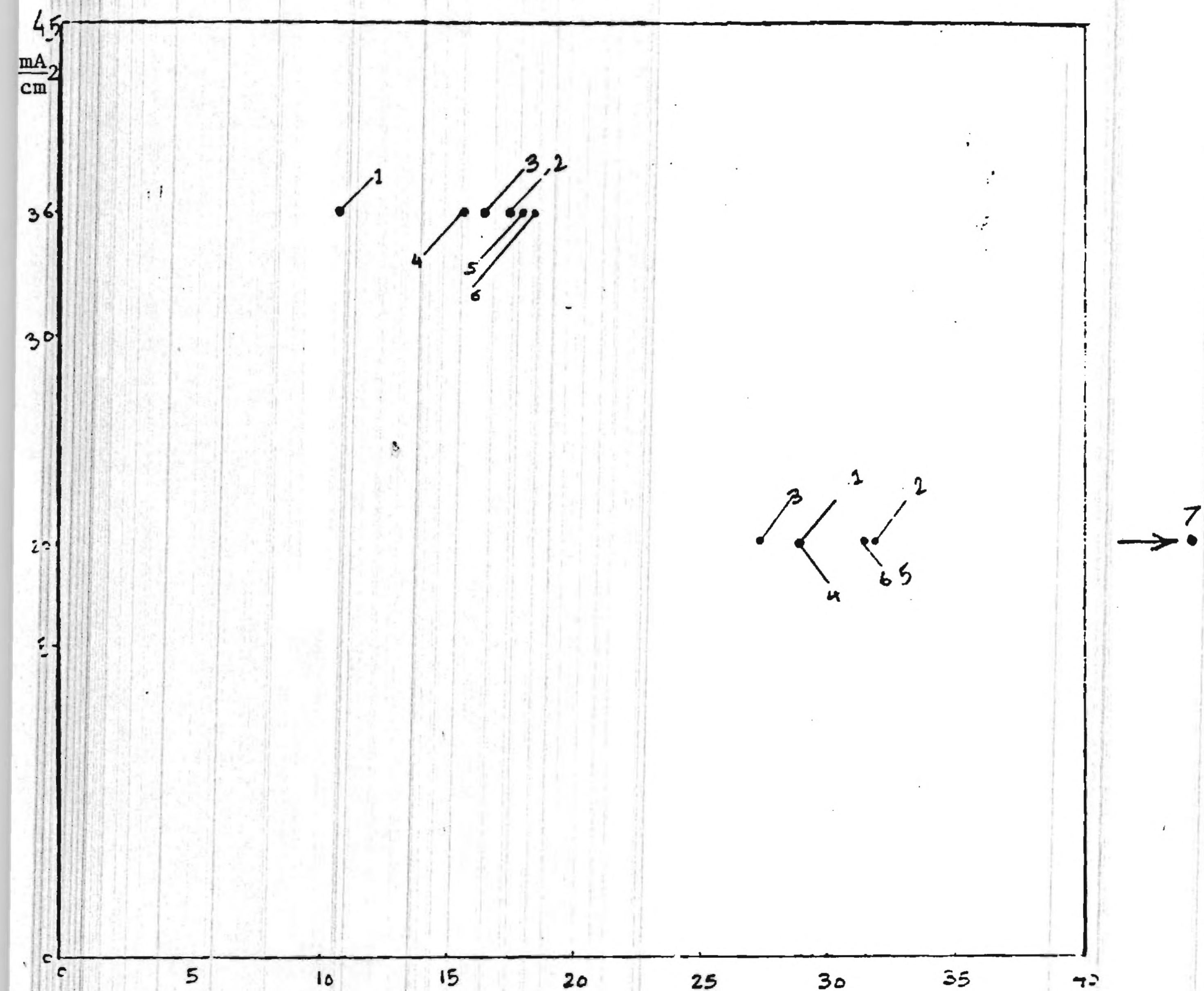
Samples	20-1	20-2	21-1	21-2	22-1	22-2
Current Applied (I, mA)	87	97	96	73	77	56
Electrochemical Life (Hrs)	10.5	17.5	16.5	16	18	19

TABLE 3

Samples	Applied Current (mA)	Potential Range (v)
20-1	87	14-16
20-1	42	9-14
20-2	97	8-10
20-2	41	7-8
21-1	96	9-10
21-1	47	8-12
21-2	73	8-9
21-2	48	8-9
22-1	77	9-14
22-1	50	8-10
22-2	56	8-9
22-2	42	7-8

TABLE 4.

Sample	Tafel Slope (v/dec)
20-1	2.90
20-2	2.20
21-1	4.95
21-2	2.15
22-1	2.35
22-2	1.65



ELECTRODE LIFE Hours

FIGURE 1.

1. 20 % KJB and 1 % Stabilizer
2. 20 % KJB and 2 % Stabilizer
3. 21 % KJB and 1 % Stabilizer
4. 21 % KJB and 2 % Stabilizer
5. 22 % KJB and 1 % Stabilizer
6. 22 % KJB and 1 % Stabilizer
7. 20 % KJB and 2 % Stabilizer hand mixed and extruded lab sample 70 + hours life

FINAL RESEARCH REPORT
TASK HR–22

CONDUCTIVE POLYMER DEVELOPMENT FOR MINESWEEPING ELECTRODE JACKETS

By

R. F. Hochman, M. Marek, J. G. Rinker, R. Pun and M. Shoaee
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School of Electrical Engineering

Prepared for

NAVAL COASTAL SYSTEMS CENTER
MINESWEEPING DIVISION
Panama City, Florida 32401

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GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
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CONDUCTIVE POLYMER DEVELOPMENT FOR

MINESWEEPING ELECTRODE JACKETS

by

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FOREWORD

This program was designed to evaluate and determine the range of variables to develop the best properties of carbon (KJB)-stabilized Hytrel conductive polymer systems. The KJB-stabilized Hytrel is the simplest and most straight forward of all the prospective electrode systems. Laboratory studies of samples have shown such a system can have a potential effective life in the neighborhood of 70 hours at 20 mA/cm^2 current density and 48 hours at 36 mA/cm^2 current density.

The major features of this system are its low cost, relative ease of fabrication and potential manufacturability, plus the potential ease of repair and rejacketing once its lifetime has been exceeded. The problem areas are: it's limited life, nonuniformity of distribution of additives and potential problems in developing uniform manufacturing procedures for the base material so full size electrodes can be manufactured with an effective conductive jacket.

The preliminary studies indicated the Hytrel stabilizer raises the potential life of this system into an acceptable range. However, to achieve an effective material, one must consider the electrical resistivity, thermal conductivity, mechanical properties and last, but not least, the electrochemical life of the system.

To accomplish this, a program was designed to optimize the range of composition for the best overall properties for electrode applications and to use pilot plant manufacturing to prepare materials for testing. Specific testing apparatus and procedures were developed to test the thermal conductivity and electrochemical life in addition to standard laboratory methods for electrical resistivity and mechanical property tests. The results of the program give a thorough evaluation of where we presently are in the potential manufacturability of such materials, including the limitations, problems, and the potential for improvements to make a conductive polymer system viable for electrode jackets.

Experiments conducted in the HR-01, the preliminary study of "Conductive Polymer Jacket Materials," indicated three potentially effective systems. These systems are: (1) stabilized-Hytrel loaded with Ketjenblack carbon, (2) platinized or palladiumized graphite loaded in stabilized Hytrel and (3) stabilized Hytrel loaded with KJB with a partial coverage of platinized or palladiumized metal strips or buttons to act as the major conductor to the sea water and to act as the surface for the electrochemical reaction. Preliminary data for these systems are shown in Table 1, under Section 2, 4, and 6.

These studies indicated that all three of these basic systems rated as positive prospects but each system must be developed further to evaluate their total potential for manufacturability, lifetime and cost as well as their thermal, electrical and mechanical properties developed before the best potential system can be selected.

Because of the directness of the approach and its relatively low cost, the Navy decided to concentrate on the system of stabilized Hytrel loaded with KJB carbon as the conducting agent. This is the simplest and most straightforward of all the prospective electrode systems, and laboratory materials indicated a potential effective life in the neighborhood of 70 hours at 20 mA/cm^2 current density and 48 hours at 36 mA/cm^2 current density. This increase is more than tenfold over previous materials and is based strictly on the addition of an effective stabilizing agent for the Hytrel. The absorption of moisture within the Hytrel plays a great part in reduction of its stability when acting as a conductive electrode material.

To evaluate the major variables in this system a grid was developed to develop materials for preliminary evaluation and to localize the areas

TABLE 1

Summary of Polymer Electrode Studies - Hytrel Polyester

Description of Composition	Filler Concentration (weight %)	Resistivity (ohm-cm)	Mechanical Properties	TEST Life Estimate (hours)
1) Non-stabilized Hytrel, filler: Ketjenblack (KJB) and Activated Carbon with 10% Pt (Pt-C)	13 KJB 12 Pt-C	12	good to excellent	15
2) Hytrel with 10MS stabilizer, filler: Ketjenblack	20	150	good to excellent	70
3) Non-stabilized Hytrel, filler: platinum black	67	200	fair to poor	200
4) Hytrel with 10MS stabilizer, filler: platinum black	67	26.5	fair to poor	> 200
5) Non-stabilized Hytrel, filler: KJB and embedded platinum strip	20 KJB 2.5 area % exposed Pt	14 (matrix)	good	25
6) 10MS-stabilized Hytrel, filler: KJB and embedded platinum strip	20 KJB 8.5 area % exposed Pt	14 (matrix)	good	>200

of principal stabilizer and KJB carbon concentrations for indepth study. This grid is shown in Table 2 and contains preliminary evaluations of several materials indicating the localization research should be in the areas of 17.5 to 22% KJB carbon and 1 to 2% hydrolytic stabilizer. Therefore the main focus of research in the balance of this program has concentrated on these materials.

TABLE 2

CHART OF POTENTIAL COMPOUNDS TO BE STUDIED
WITH PRELIMINARY EVALUATION OF TEST MATERIALS

<table>
<tr><th rowspan="2">% KJB Carbon</th><th colspan="4">% Stabilizer</th></tr>
<tr><th>1</th><th>2</th><th>4</th><th>6</th></tr>
<tr><td>22</td><td rowspan="4">Potential Material
See Experimental Results</td><td rowspan="4">Potential Material
See Experimental Results</td><td rowspan="3">Compound Highly
Embrittled</td><td rowspan="4">Attempted, but could
not compound</td></tr>
<tr><td>21</td></tr>
<tr><td>20</td></tr>
<tr><td>17.5</td><td></td></tr>
<tr><td>15</td><td colspan="2">Low Conductivity</td><td></td><td></td></tr>
</table>

1.2 ELECTRICAL CONDUCTIVITY

The initial physical property of importance was the ability of the material to conduct electrical current. If the general mechanical properties appeared satisfactory, the resistivity of the material was the next major factor to be examined.

Extruded samples of carbon-filled polymer were tested for electrical resistivity. Cylindrical specimens were tightly fixed in compression between two copper supports. DC current was passed through the specimens and the voltage drop between the copper supports was measured. To minimize error due to the contact resistances between the specimen and the copper supports, a thin layer of a conductive, carbon-filled grease was applied to the contacting surfaces. The contact pressure was 20 psi.

The resistivity of the material was calculated from the formula:

$$\rho = VA/(IL)$$

where V is the measured voltage drop, A is the cross-sectional area of the sample, I is the current applied and L is the length of the specimen.

All samples except Hytrel 20-1 were machined to a diameter of approximately 0.725 cm and were approximately 1 cm long. The actual length and diameter were accurately measured with a high precision micrometer. The current was adjusted on all samples to produce a current density, 0.24 mA/cm^2 and the compressive stress of 20 psi was used for all samples.

The data for composition versus electrical resistivity is tabulated in Table 3. Figure 1 is a plot of the electrical resistivity of the Hytrel base compounds as a function of percent carbon additive by weight. The electrical resistivity of the Hytrel compounds was measured with applied current density in the range from 0.24 mA/cm^2 to 0.024 mA/cm^2.

This data is tabulated in Tables 4, 5, 6, 7, 8 and 9. Figure 2 is a plot of electrical resistivity as a function of the applied current.

Table 3. Summaries of Resistivity for Hytrel of Varies Carbon and Stabilizer Content.

Polyester Elastomer Hytrel*	Diameter cm.	Length cm.	Current ampere	Voltage volt	Resistivity ohm-cm
20-1	0.892	1.212	$1X10^{-4}$	$2.7X10^{-3}$	13.9
20-2	0.727	1.550	$1X10^{-4}$	$1.08X10^{-3}$	3.0
21-1	0.727	0.879	$1X10^{-4}$	$2.90X10^{-3}$	13.7
21-2	0.727	2.102	$1X10^{-4}$	$2.85X10^{-3}$	6.0
22-1	0.727	0.981	$1X10^{-4}$	$2.02X10^{-3}$	13.0
22-2	0.727	1.203	$1X10^{-4}$	$1.50X10^{-3}$	5.2

* The first number signifies the weight percentage of carbon black and the second number signifies the weight percentage of stabilizer.

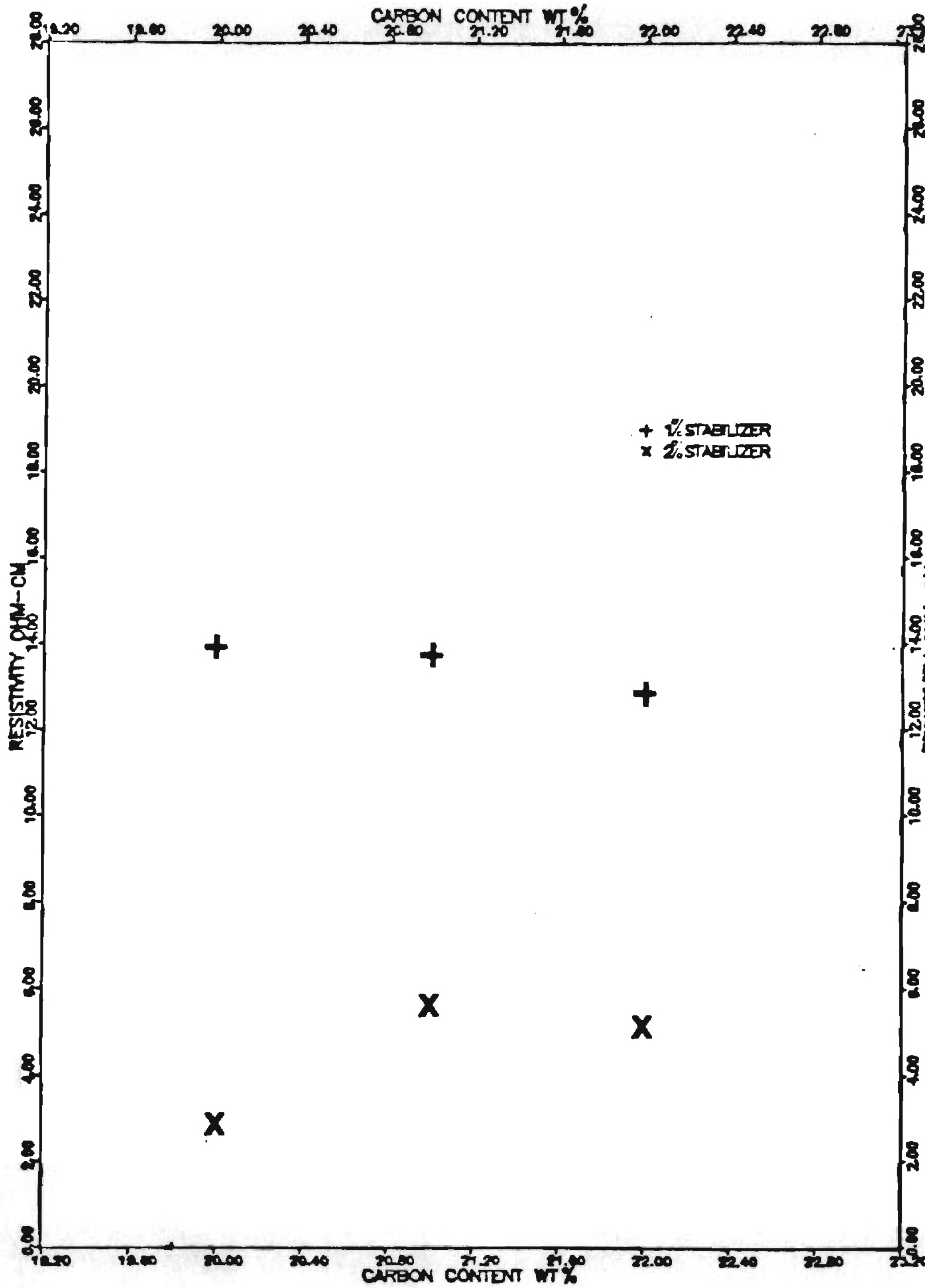


Figure 1. Resistivity of Hytrel-graphite Compounds as a Function of Stabilizer and Carbon Content

TABLE 4 . Current Density versus Resistivity for Hytrel 20-1

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	2.7	13.9
0.217	2.4	13.8
0.169	1.9	13.6
0.096	1.1	13.9
0.024	0.3	13.9

TABLE 5. Current Density versus Resistivity for Hytrel 20-2

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	1.1	2.8
0.217	0.9	2.6
0.169	0.7	2.6
0.096	0.4	2.7
0.024	0.1	2.7

TABLE 6 . Current Density versus Resistivity for Hytrel 21-1

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	2.9	13.9
0.217	2.6	13.6
0.169	2.0	13.5
0.096	1.2	13.9
0.024	0.3	14.2

TABLE 7 . Current Density versus Resistivity for Hytrel 21-2

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	2.9	5.6
0.217	2.6	5.6
0.169	2.0	5.6
0.096	1.2	5.7
0.024	0.3	5.7

TABLE 8. Current Density versus Resistivity for Hytrel 22-1

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	2.5	12.9
0.217	2.2	11.3
0.169	1.7	11.5
0.096	1.0	11.5
0.024	0.3	12.1

TABLE 9. Current Density versus Resistivity for Hytrel 22-2

Current Density mA/cm^2	Voltage mV	Resistivity ohm-cm
0.241	1.5	5.3
0.217	1.3	5.0
0.169	1.0	5.0
0.096	0.6	5.1
0.024	0.15	5.2

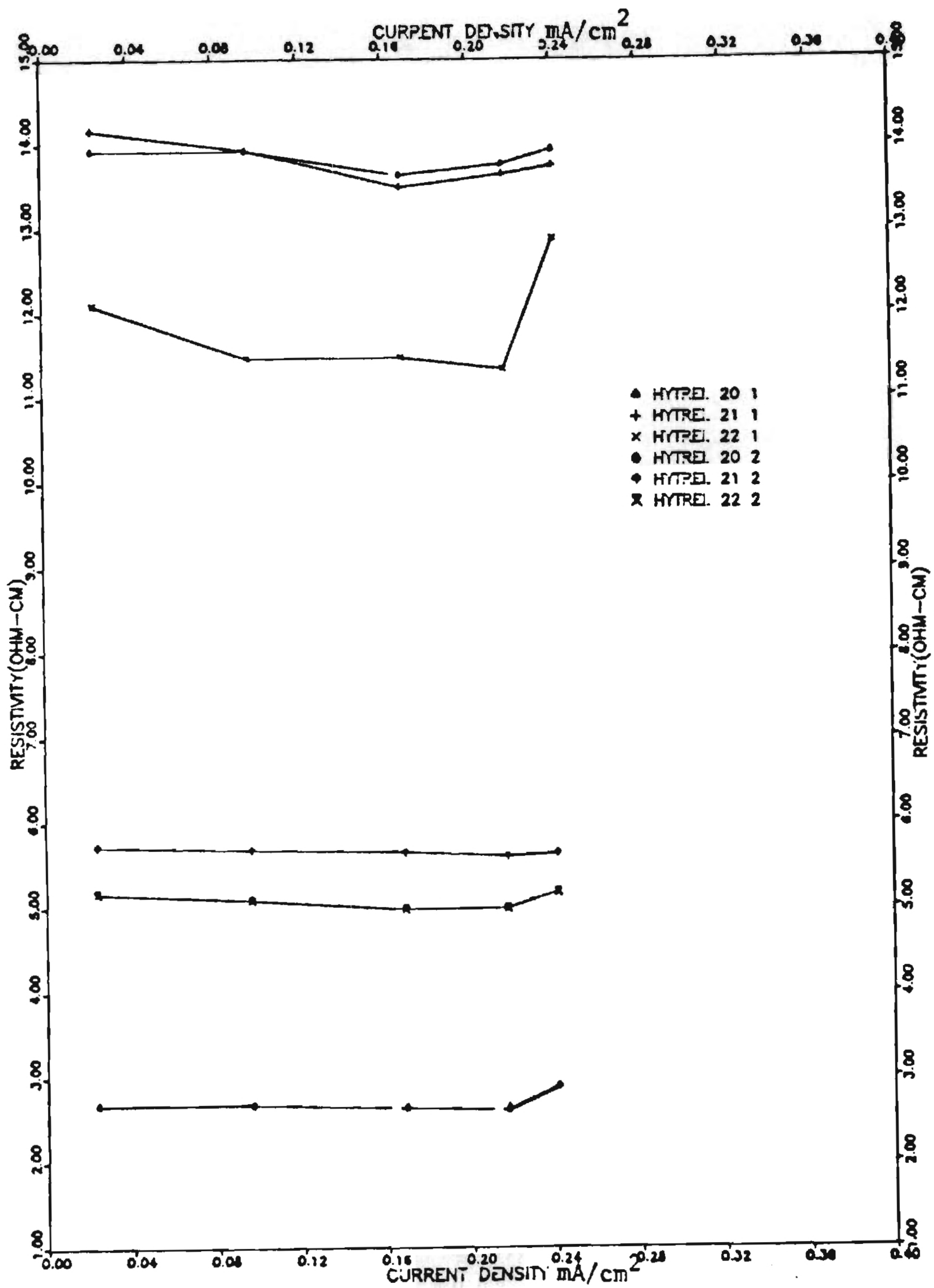


Figure 2. Electrical Resistivity of Polyester Elastomer (Hytrel) as a Function of Current Density

1.3 THERMAL CONDUCTIVITY MEASUREMENTS

A high thermal conductivity is desired for the electrical conductive polymer and is crucial to a jacketed electrode design. Should the conductivity be lower than the rate of heat generation in the aluminum jacketed electrode, thermal deterioration may cause deterioration or even explosion of the conductive jacket. The conductive Hytrel jacket will be a thin-walled cylindrical tube of thickness ranging from one to two millimeters.

The measurement of thermal conductivity by using a uniform sheet of material of thickness B and cross-sectional area A whose faces are kept at constant temperatures T_1 and T respectively where T_1 is greater than T. Heat is then conducted through the sample from the face at the higher temperature to the face at the lower temperature. If the sample is thermally insulated so that no heat escapes from the sides, then the lines of heat flow are perpendicular to the faces and the amount of heat conducted across any cross-section of the sample is effectively constant.

The rate of heat flow R is the quantity of heat flowing through the slab per unit time. R is directly proportional to the temperature difference (T_1-T) and the cross-sectional area A, but inversely proportional to the thickness B:

$$R = KA\,(T_1-T)/B$$

K, the factor of proportionality, is of course the thermal conductivity of the material.

The calculations are based on a thin slab or sheet of conductive polymer between a constant temperature source and a receiver consisting of a thermally insulated cylindrical block of copper (thermal capacity equals to 0.093 calorie per gram). The upper face of the sample is at a constant temperature T_1, while the temperature T of the lower face is slowly changing. Consider that in a small interval of time dt the temperature of the copper block receiver change by a small amount dT_i where T_i is the instantaneous temperature of the copper block. Then dT_i/dt is the rate of increase in temperature of the copper block. The number of calories per second R received by the copper block is:

$$R = Mc(dT_i/dt) \tag{1}$$

where M is the mass (340 grams) and c is the specific heat of the copper block. If no heat escapes from the copper block, the amount of heat conducted through the specimen per unit time is equal to the number of calories received by the copper block per second or:

$$KA(T_1-T)/B = Mc(dT_i/dt) \tag{2}$$

where K is the thermal conductivity, B is the thickness of the specimen whose upper face has a constant temperature T_1 and whose lower face is at temperature T. A is the surface area of the heat receiving unit.

Let y be a variable proportional to the temperature difference;

$$y = A(T_1-T) \tag{3}$$

where the constant of proportionality is equal to the surface area of the copper block A. Now, if T_1 remains constant and T changes, any change in T produces a corresponding change in the variable y. Thus, if the instantaneous rate of change of the variable y with respect to time t is given by differentiation of equation (3):

$$dy/dt = A(dT_i/dt) \tag{4}$$

By substitution of equations (3) and (4) in equation (2), it follows:

$$dt = -McB/(KC) \times (dy/y) \tag{5}$$

By integration:

$$t = -McB/(KA) \times \ln(y) + K' \qquad (6)$$

To evaluate K', the constant of integration, substitute the initial conditions, $y = y_o$ at $t = 0$ min. and:

$$K' = McB/(KA) \times \ln(y_o) \qquad (7)$$

Substituting K' in equation (6), it becomes:

$$t = -McB/(KA) \times (\ln(y) - \ln(y_o)) \qquad (8)$$

A program has been developed on the CDC 70/74-6400 computer to evaluate the thermal conductivity from the experimental data. Results from five different runs were analyzed as a single evaluation and a linear regression of a least squares analysis was assumed.

A schematic drawing of the experimental apparatus is shown in Figure 3. The output was routed to a VERSATEC electrostatic plotter and plots of time versus a logarithmic function of temperature were obtained.

Carbon-filled Hytrel base polymer compounds produced from a single screw extruder were used for the thermal conductivity studies. Initially several samples of pure Hytrel were pressed into sheet for the conductivity measurements. The results were summarized in Figures 4 and 5 and Table 10. An average thermal conductivity value of 5.7×10^{-4} cal./cm./sec./deg. was determined for the base Hytrel material. Based on the general reference data, these results are representative of the conductivity of the pure Hytrel. This value was considered as the base or reference value for thermal conductivity in comparison to data on the carbon-filled Hytrel polymers. The results show that the heat conduction rate remained relatively constant for the first eight to ten minutes, then decreased with respect to time. The deflection of the time-temperature response at high temperature is mainly due to the decrease in the driving force for

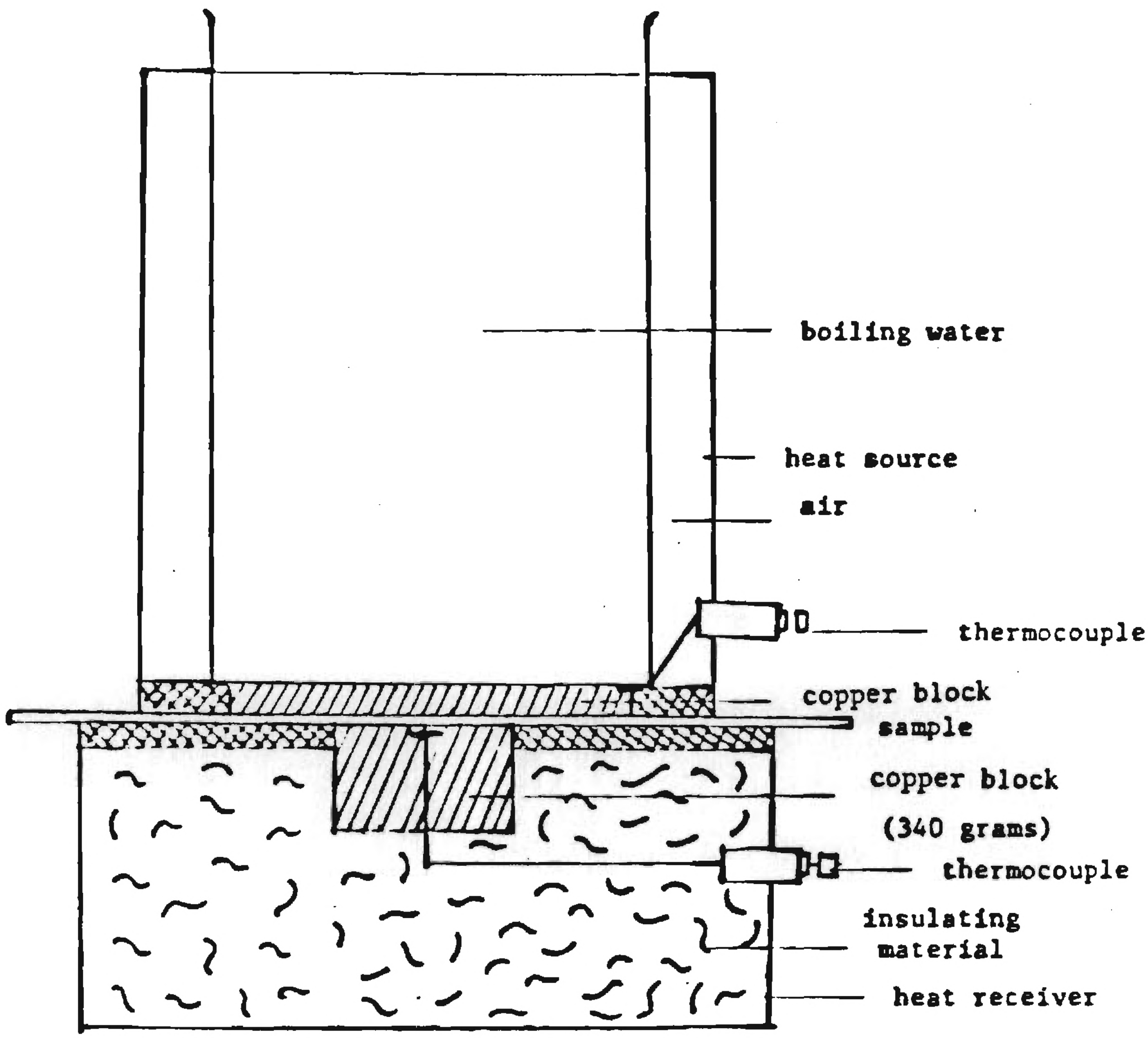


Figure 3. Schematic Sketch of Thermal Apparatus Setup

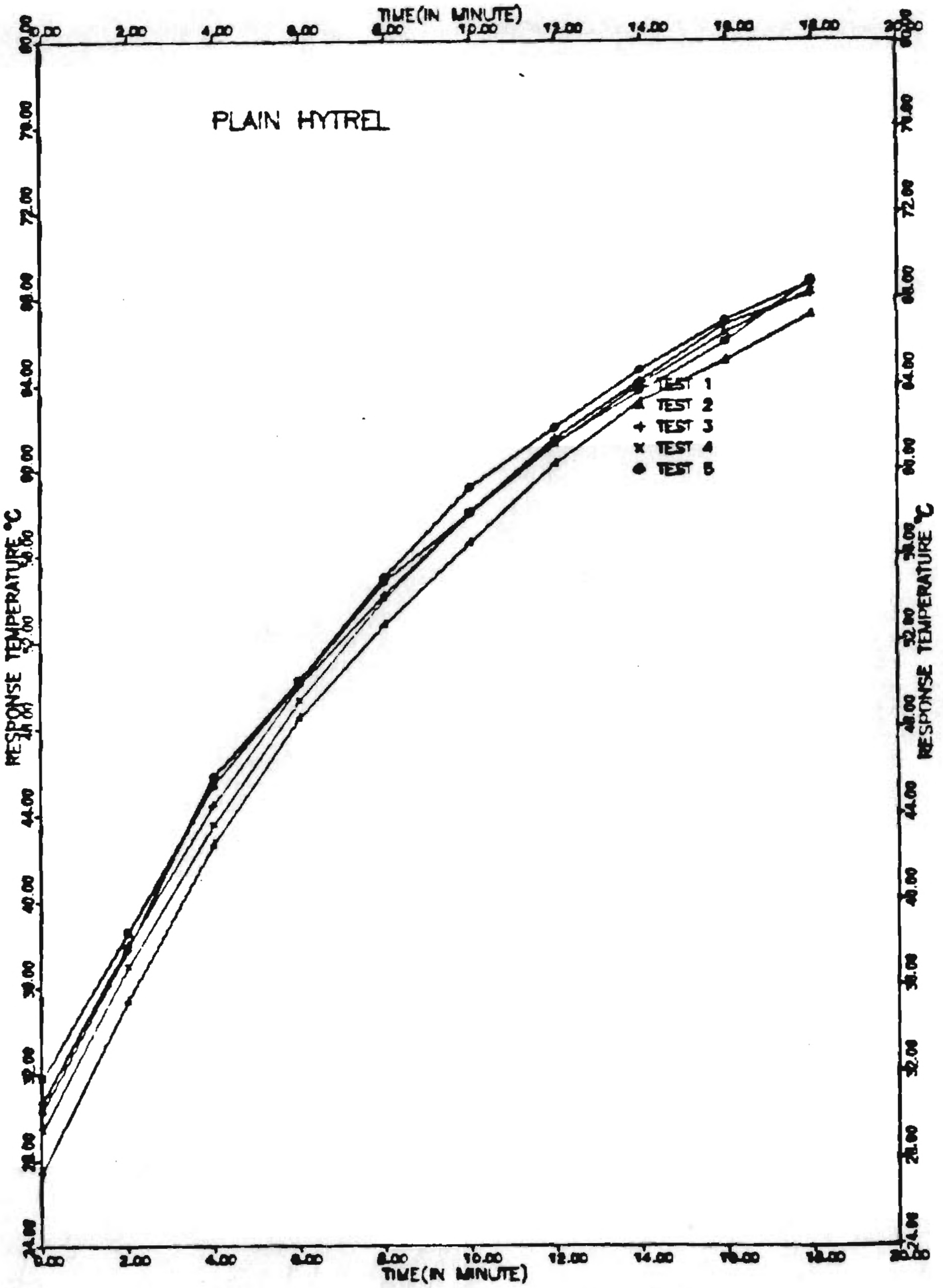


Figure 4. Time-Temperature Response Curve for Plain Hytrel

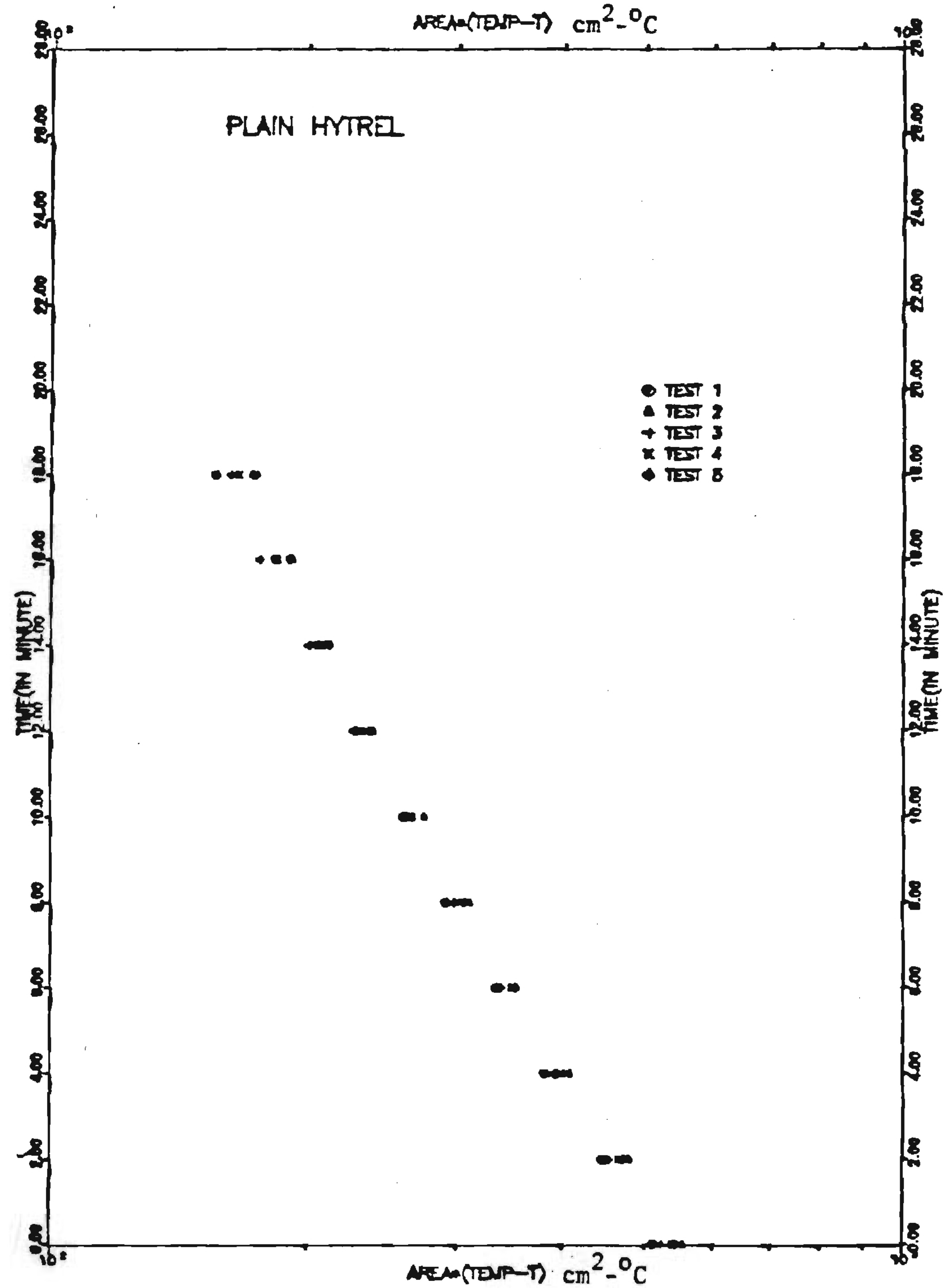


Figure 5. Time-Temperature Response in accordance with Equation (8) for Plain Hytrel

TABLE 10. Thermal Conductivity for Plain Polyester Elastomer (Hytrel)

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY Btu/hr/ft/F	cal/cm/sec/deg	$kg.m./sec^3/K$
1	$1.3X10^{-1}$	$5.6X10^{-4}$	$2.3X10^{-1}$
2	$1.4X10^{-1}$	$5.7X10^{-4}$	$2.4X10^{-1}$
3	$1.4X10^{-1}$	$5.8X10^{-4}$	$2.4X10^{-1}$
4	$1.4X10^{-1}$	$5.8X10^{-4}$	$2.4X10^{-1}$
5	$1.4X10^{-1}$	$5.6X10^{-4}$	$2.4X10^{-1}$
AVERAGE	$1.4X10^{-1}$	$5.7X10^{-4}$	$2.4X10^{-1}$
STANDARD DEVIATION	$2.8X10^{-3}$	$1.1X10^{-5}$	$4.1X10^{-3}$

heat conduction because the temperature at the receiver was approaching that of the heat source. The decreasing temperature difference between the two surfaces inevitably leads to a decrease in the rate of heat conduction. Figure 5 shows the time-temperature response in accordance with equation (8) for plain Hytrel. The slope of the best fit straight line through the data points is proportional to the reciprocal of the thermal conductivity. The representative thermal conductivity was determined by averaging the results of the various test runs.

In order to study the stabilizer effect on the thermal conductivity measurements, Hytrel samples containing 20%, 21%, and 22% KJB and 1% and 2% stabilizer were investigated. In addition Hytrel with 17.5% KJB and 2% stabilizer was also studied. The time-temperature response for various compounds with 1% stabilizer is presented in Figures 6, 7, 8, 9, 10, and 11. Thermal conductivity data is tabulated in Tables 11, 12 and 13.

Time-temperature response histories for Hytrel containing 2% hydrolytic stabilizer and various KJB carbon content is presented in Figures 12, 13, 14, 15, 16, 17, 18 and 19. The thermal conductivity data is tabulated in Tables 14, 15, 16, and 17 for Hytrel containing 17.5%, 20%, 21%, and 22% KJB respectively. Figure 20 is a plot of thermal conductivity Hytrel 4056 as a function of KJB carbon content. The thermal property of the polymer at KJB levels below 17.5% by weight were not of interest in this work.

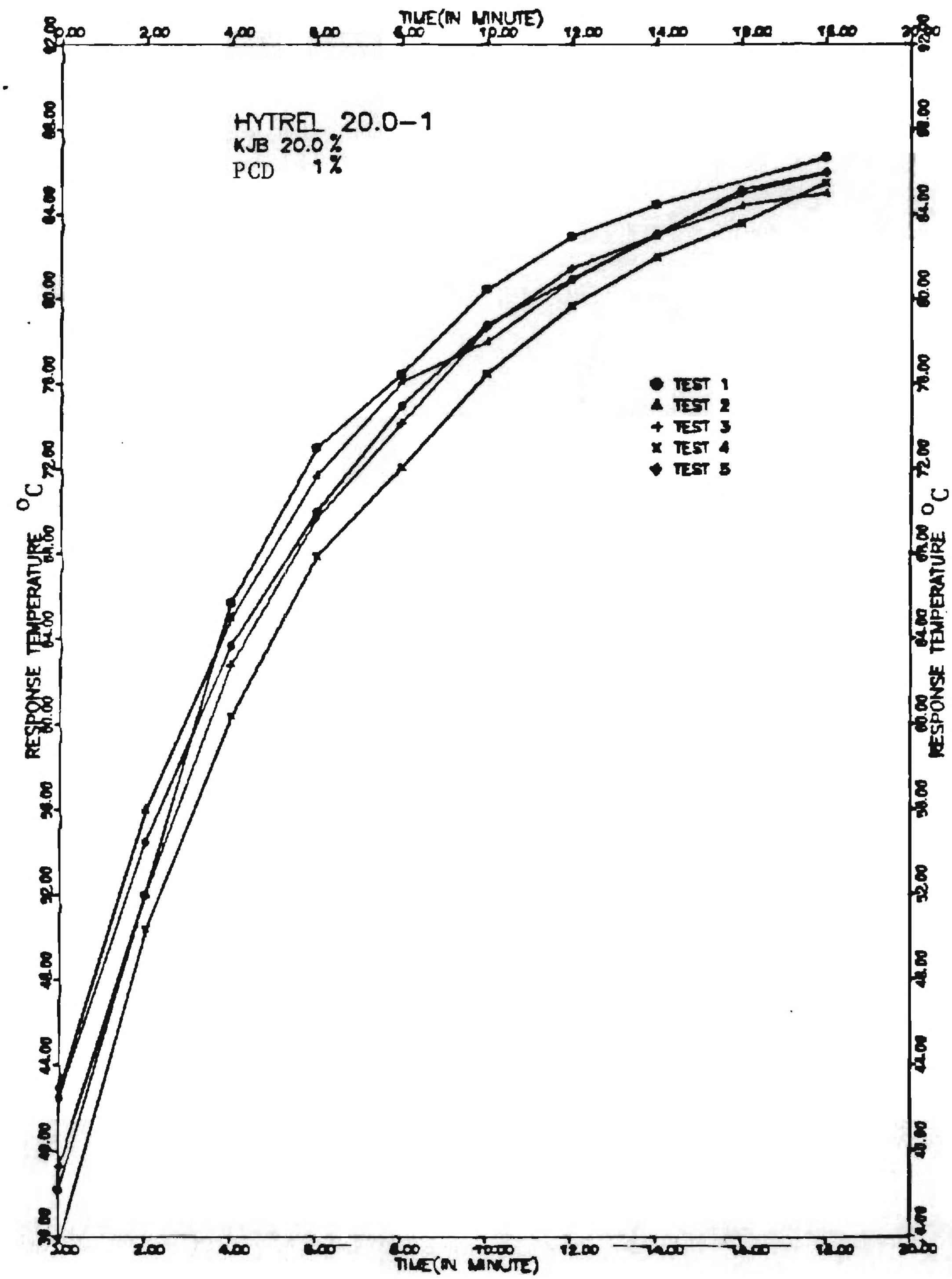


Figure 6. Time-Temperature Response Curve for Hytrel 20-1

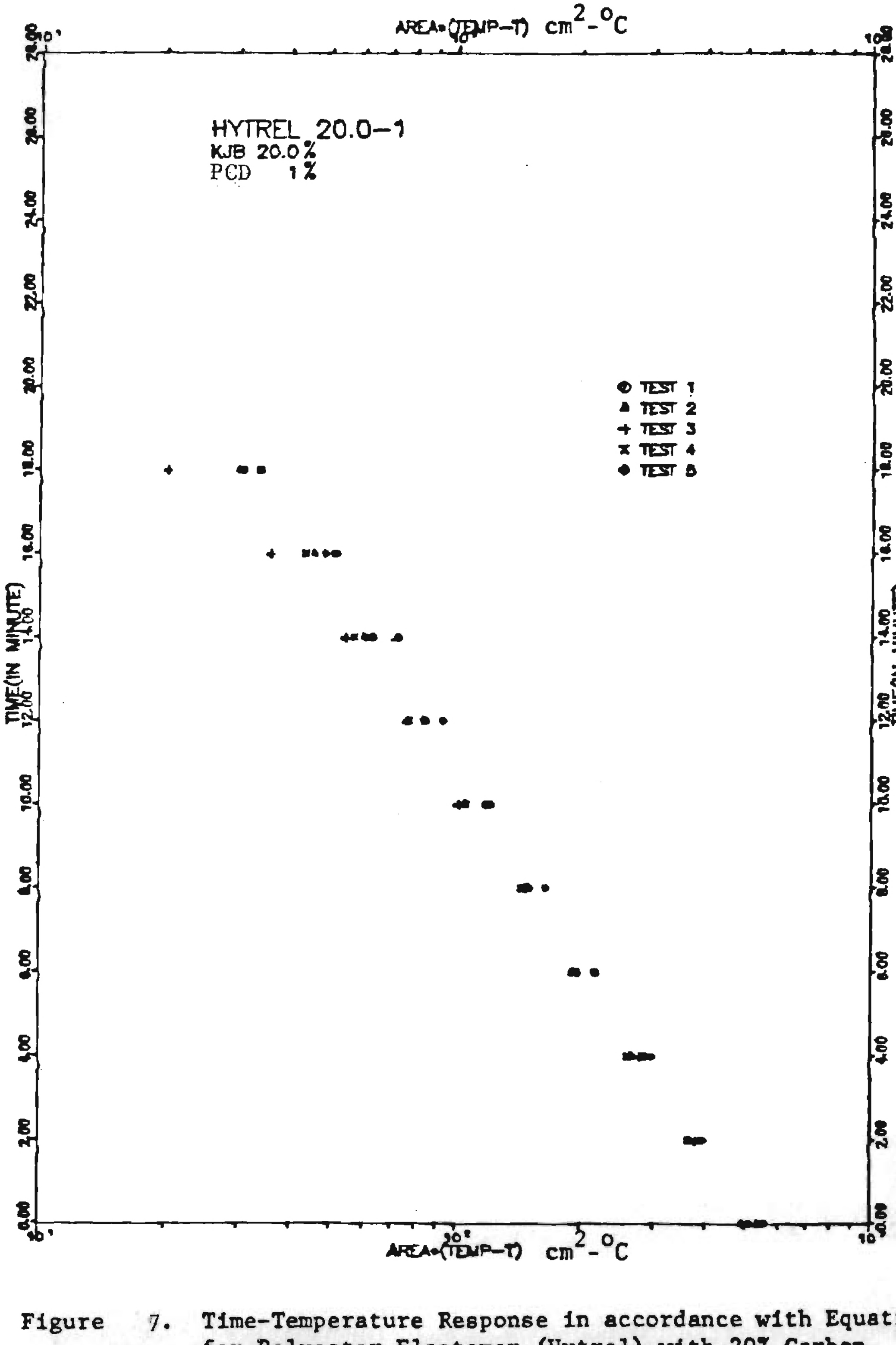


Figure 7. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 20% Carbon and 1% Stabilizer

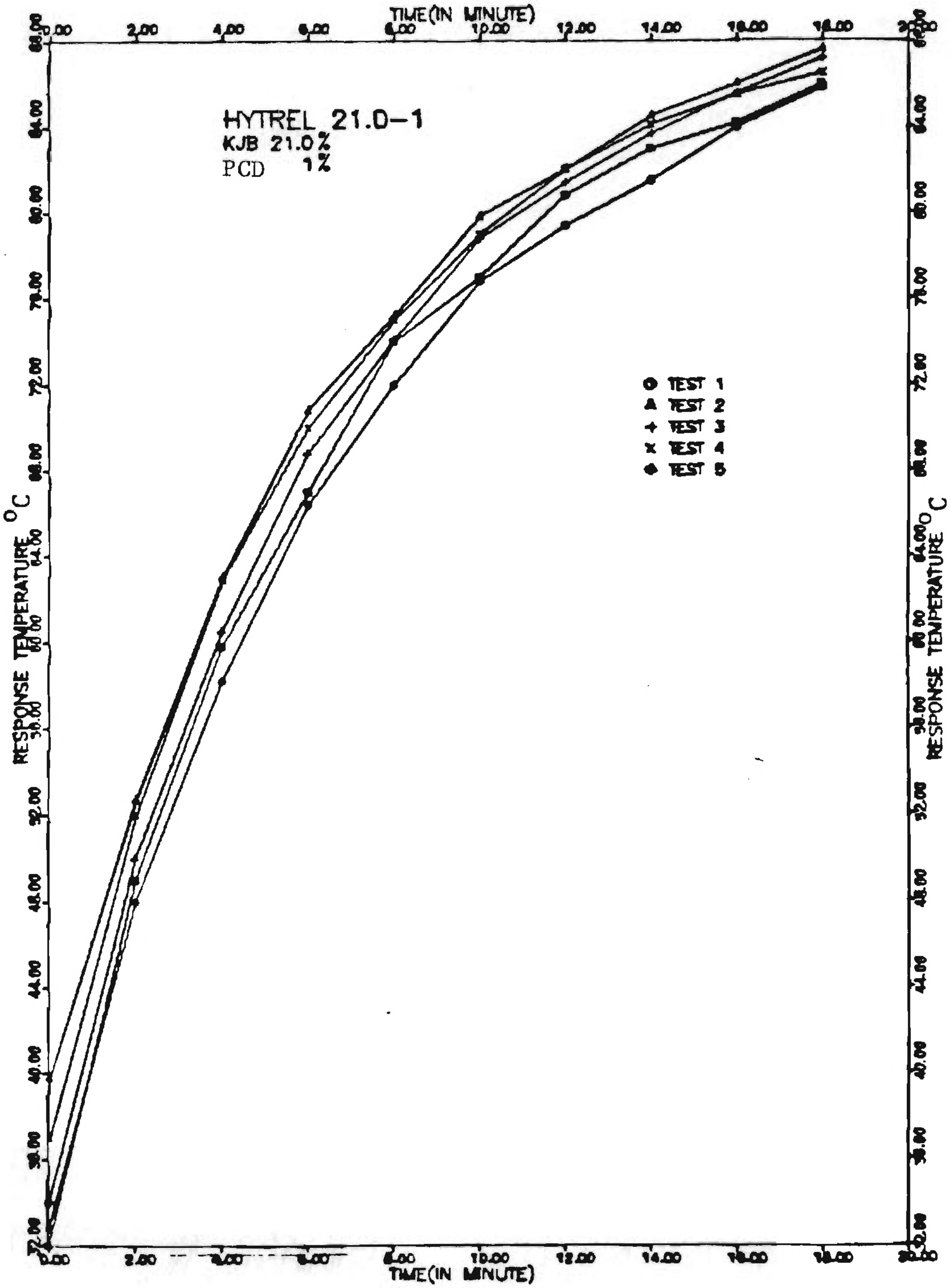


Figure 8. Time-Temperature Response Curve for Hytrel 21-1

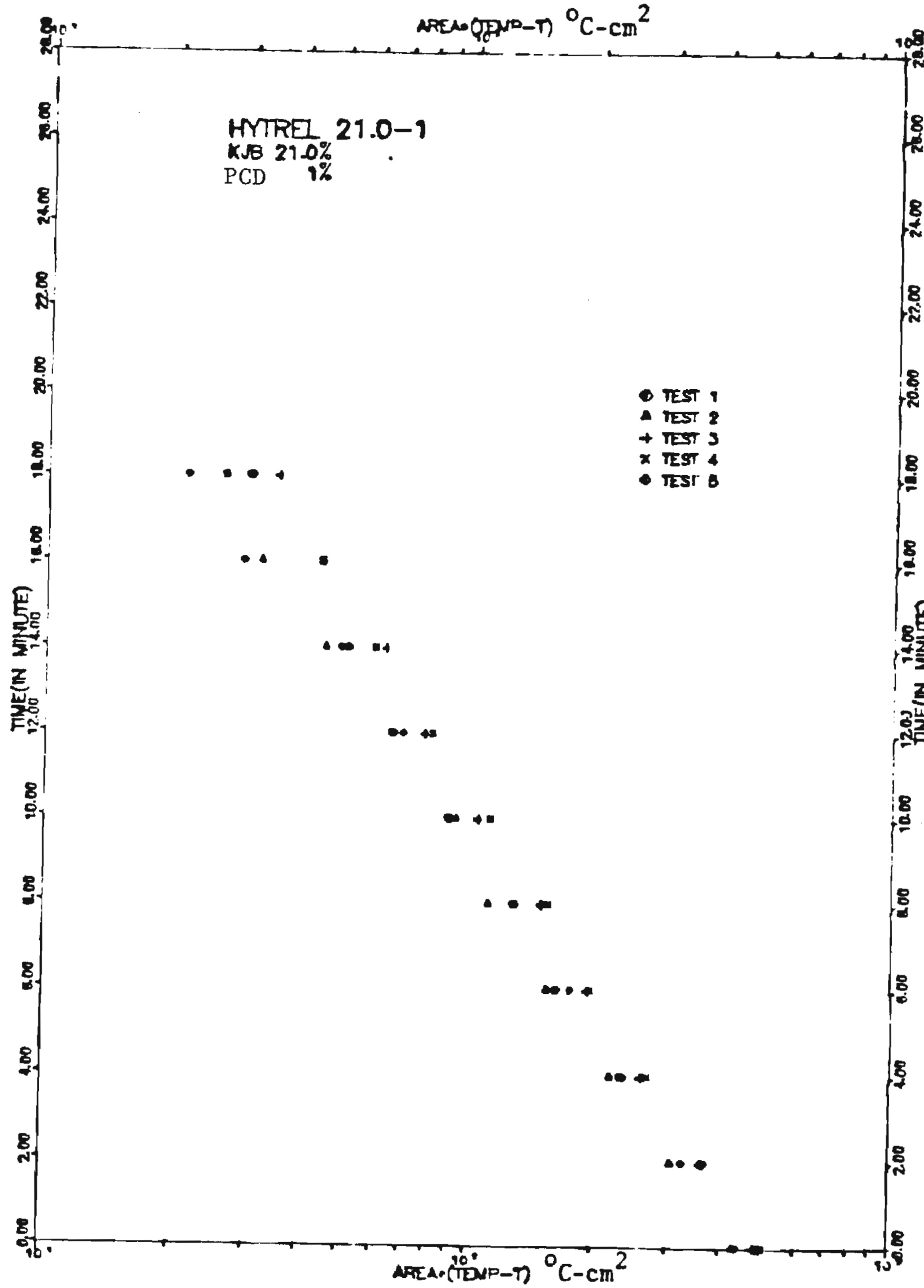


Figure 9. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 21% Carbon and 1% Stabilizer

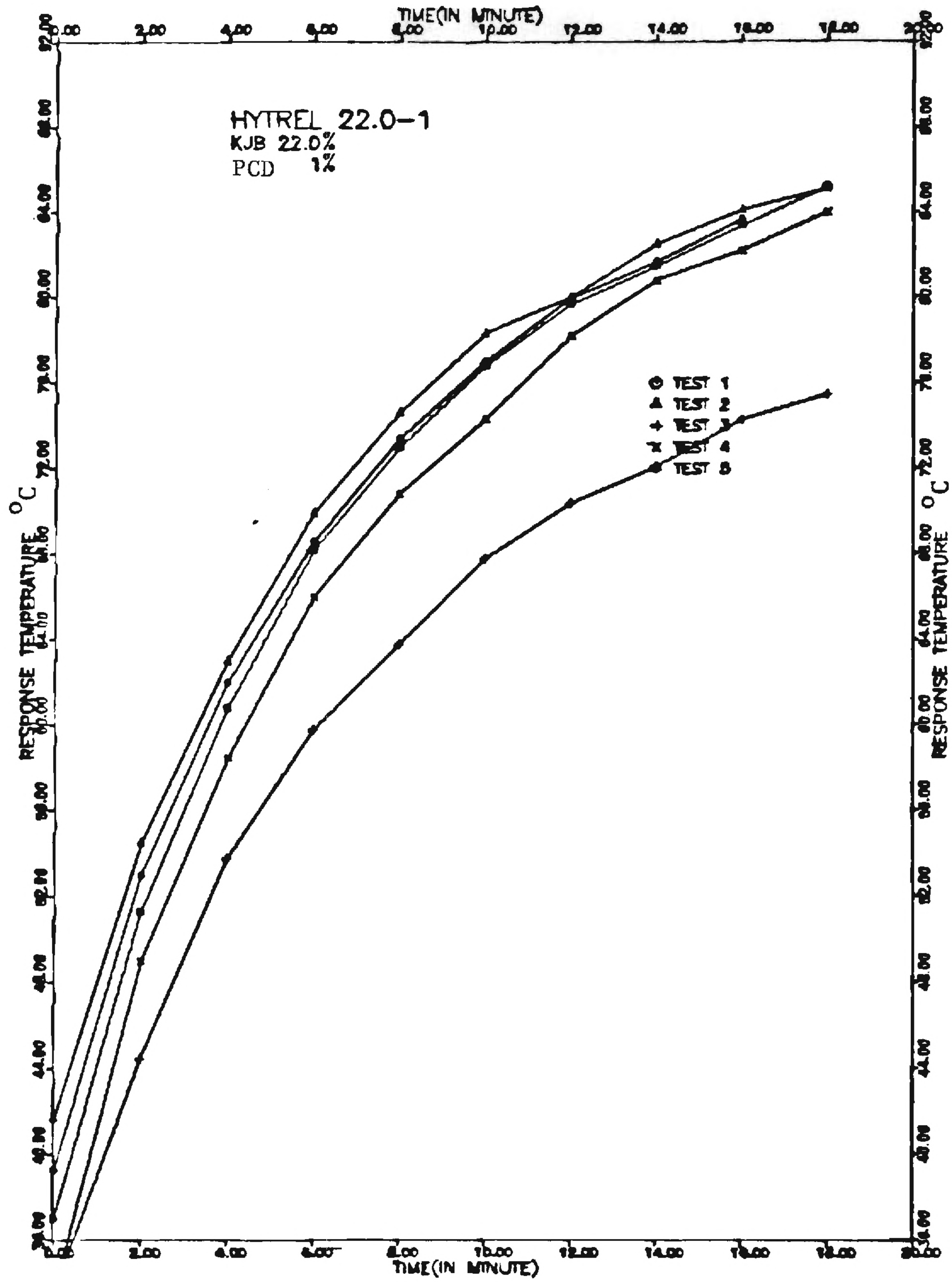


Figure 10. Time-Temperature Response Curve for Hytrel 22-1

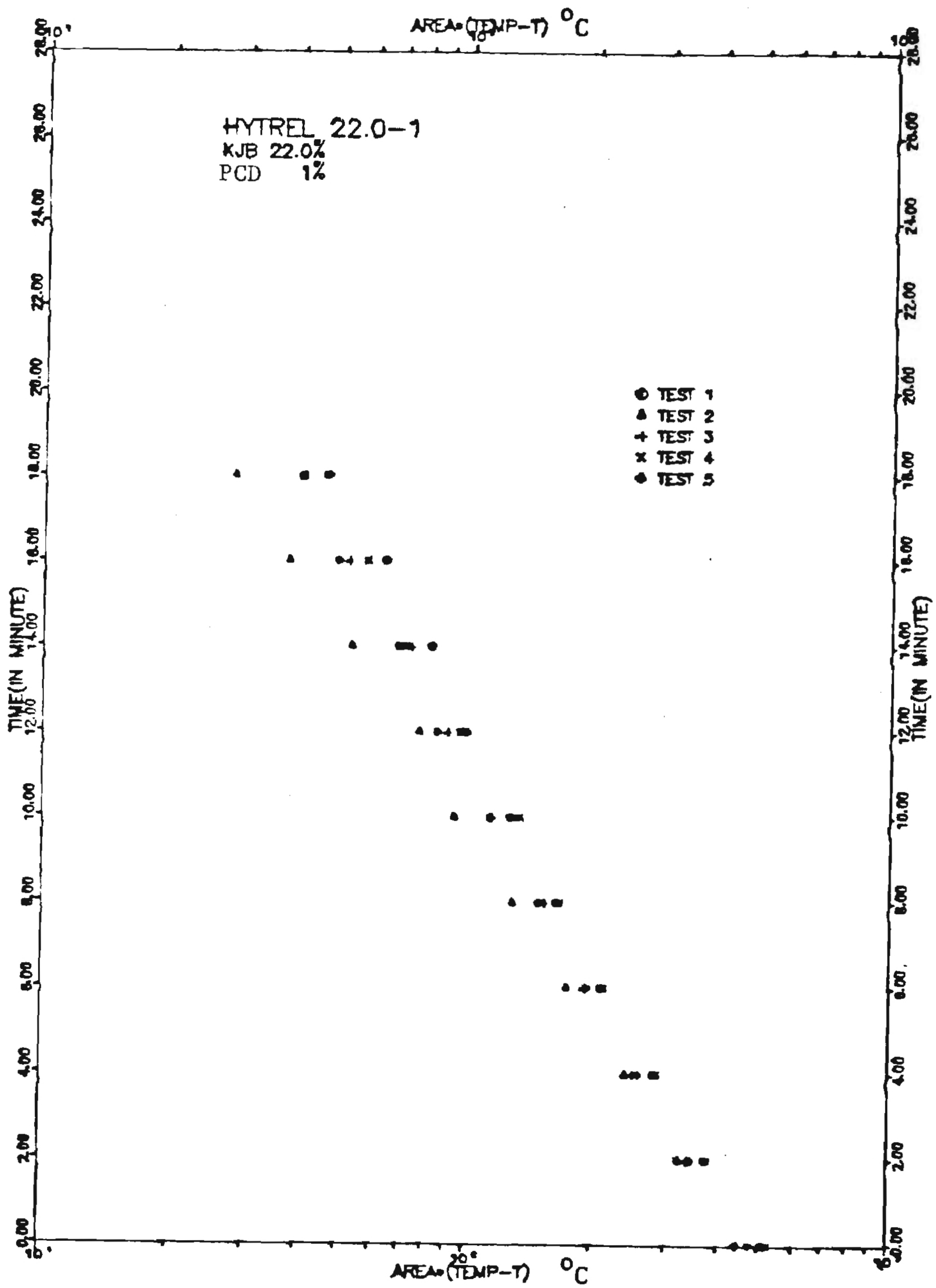


Figure 11. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 22% Carbon and 1% Stabilizer

TABLE 11. Thermal Conductivity of Polyester Elastomer with 20.0% KJB and 1% PCD

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY Btu/hr/ft/F	cal/cm/sec/deg	kg.m./sec^3/K
1	2.5×10^{-1}	1.1×10^{-3}	4.4×10^{-1}
2	2.6×10^{-1}	1.1×10^{-3}	4.4×10^{-1}
3	2.4×10^{-1}	9.9×10^{-4}	4.1×10^{-1}
4	2.6×10^{-1}	1.1×10^{-3}	4.4×10^{-1}
5	2.7×10^{-1}	1.1×10^{-3}	4.7×10^{-1}
AVERAGE	2.6×10^{-1}	1.1×10^{-3}	4.4×10^{-1}
STANDARD DEVIATION	1.1×10^{-2}	4.9×10^{-5}	2.1×10^{-2}

TABLE 12. Thermal Conductivity of Polyester Elastomer with 21.0% KJB and 1% PCD

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY Btu/hr/ft/F	cal/cm/sec/deg	kg.m./sec^3/K
1	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
2	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
3	$3.1X10^{-1}$	$1.3X10^{-3}$	$5.4X10^{-1}$
4	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
5	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
AVERAGE	$2.8X10^{-1}$	$1.2X10^{-3}$	$4.8X10^{-1}$
STANDARD DEVIATION	$1.8X10^{-2}$	$8.9X10^{-5}$	$3.1X10^{-2}$

TABLE 13. Thermal Conductivity of Polyester Elastomer with 22.0% KJB and 1% PCD

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY Btu/hr/ft/F	cal/cm/sec/deg	$kg.m./sec^3/K$
1	$2.4X10^{-1}$	$9.8X10^{-4}$	$4.1X10^{-1}$
2	$2.8X10^{-1}$	$1.2X10^{-3}$	$4.8X10^{-1}$
3	$2.4X10^{-1}$	$9.9X10^{-4}$	$4.2X10^{-1}$
4	$2.5X10^{-1}$	$1.1X10^{-3}$	$4.4X10^{-1}$
5	$2.5X10^{-1}$	$1.1X10^{-3}$	$4.4X10^{-1}$
AVERAGE	$2.5X10^{-1}$	$1.0X10^{-3}$	$4.4X10^{-1}$
STANDARD DEVIATION	$1.6X10^{-2}$	$9.1X10^{-5}$	$2.7X10^{-2}$

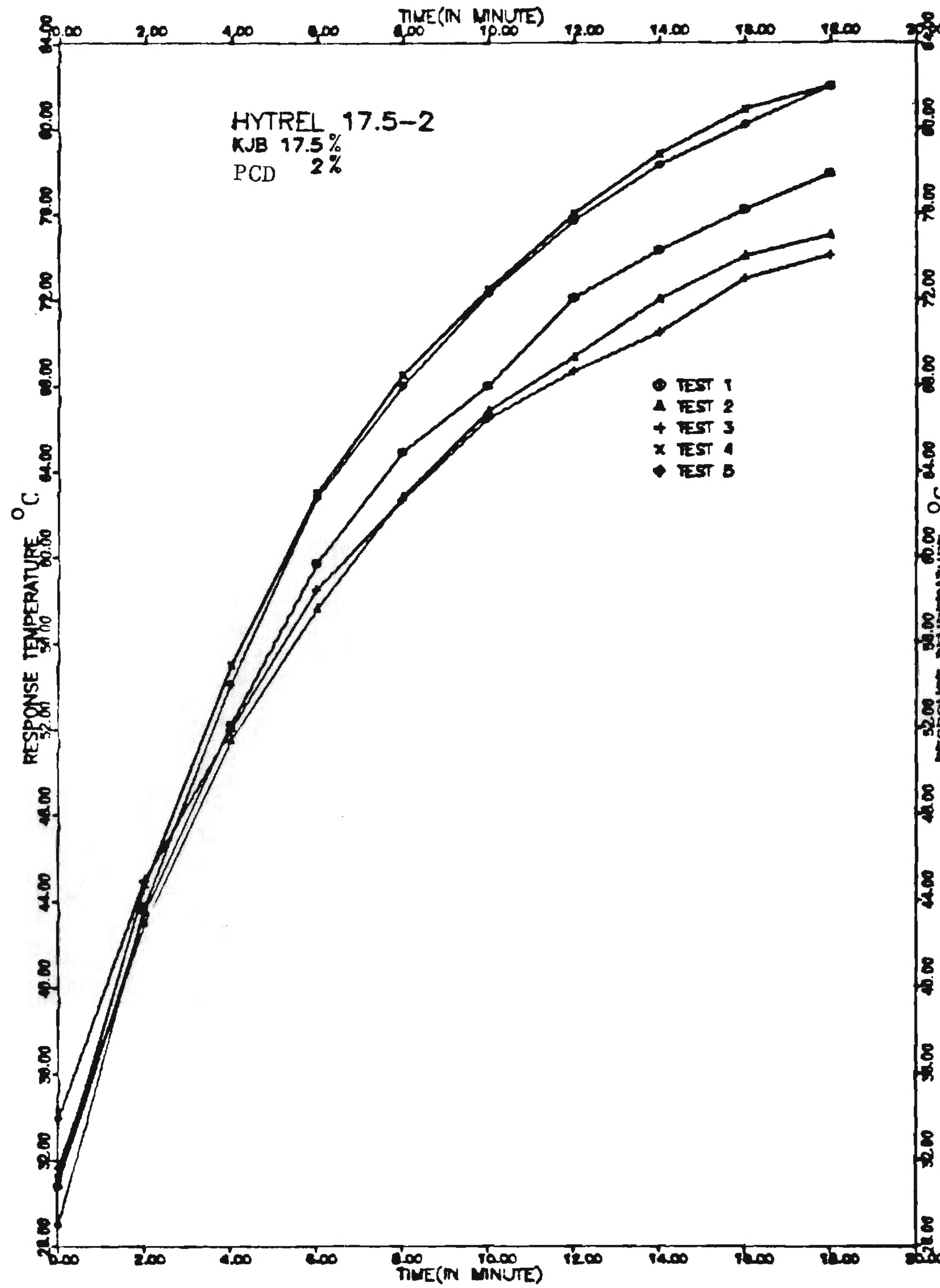


Figure 12. Time-Temperature Response Curve for Hytrel 17.5-2

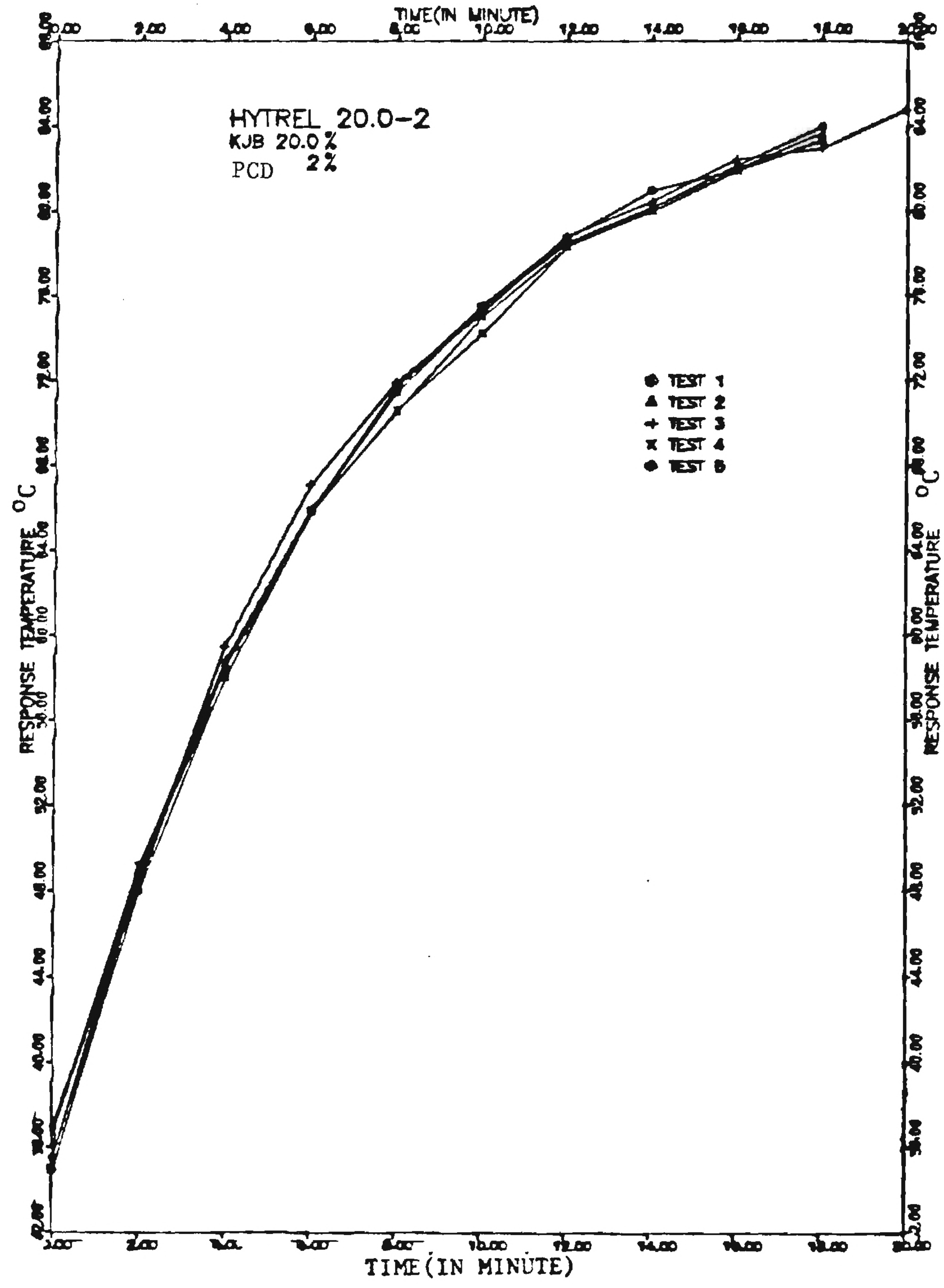


Figure 13. Time-Temperature Response Curve for Hytrel 20-2

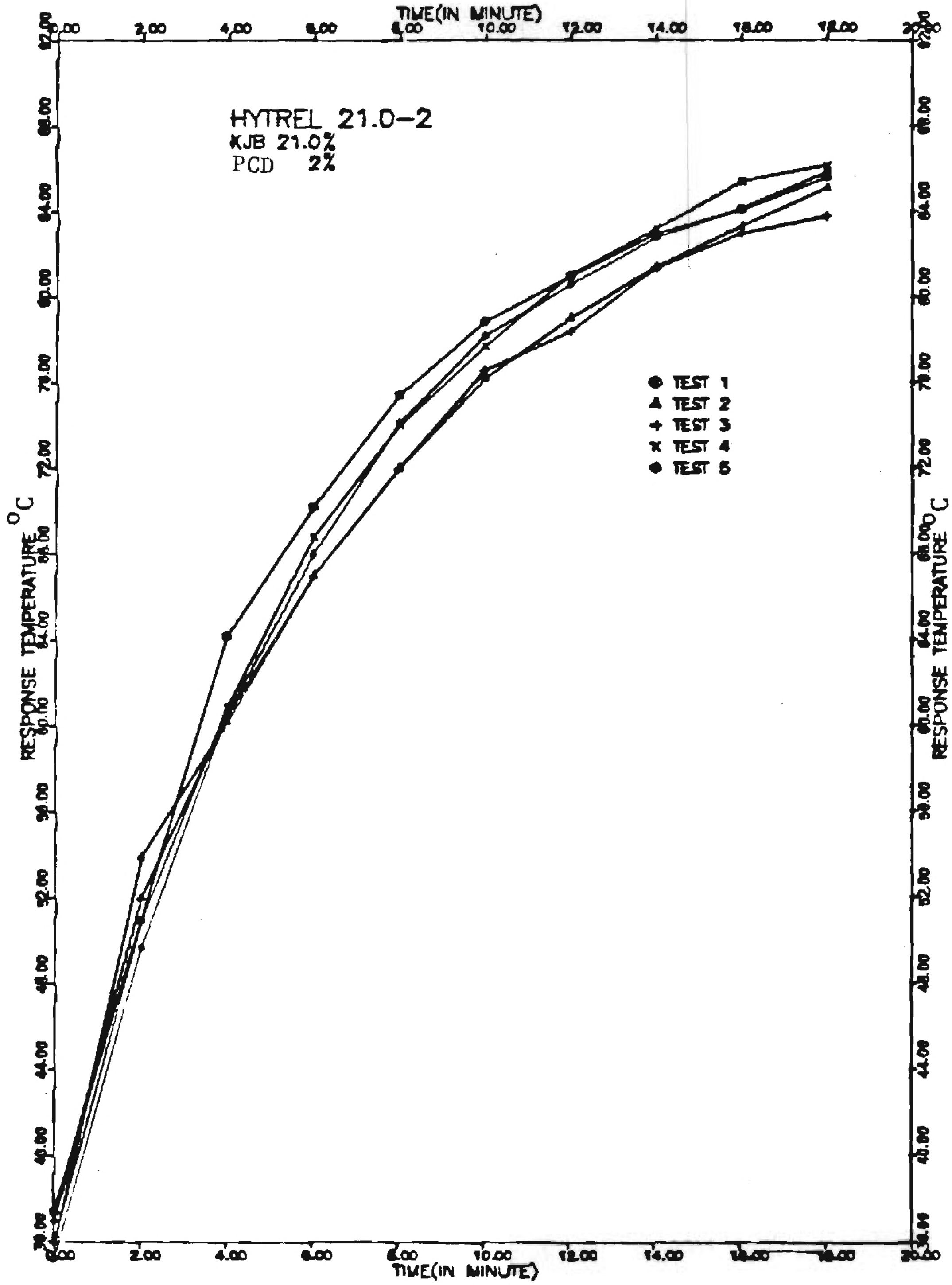


Figure 14. Time-Temperature Response Curve for Hytrel 21-2

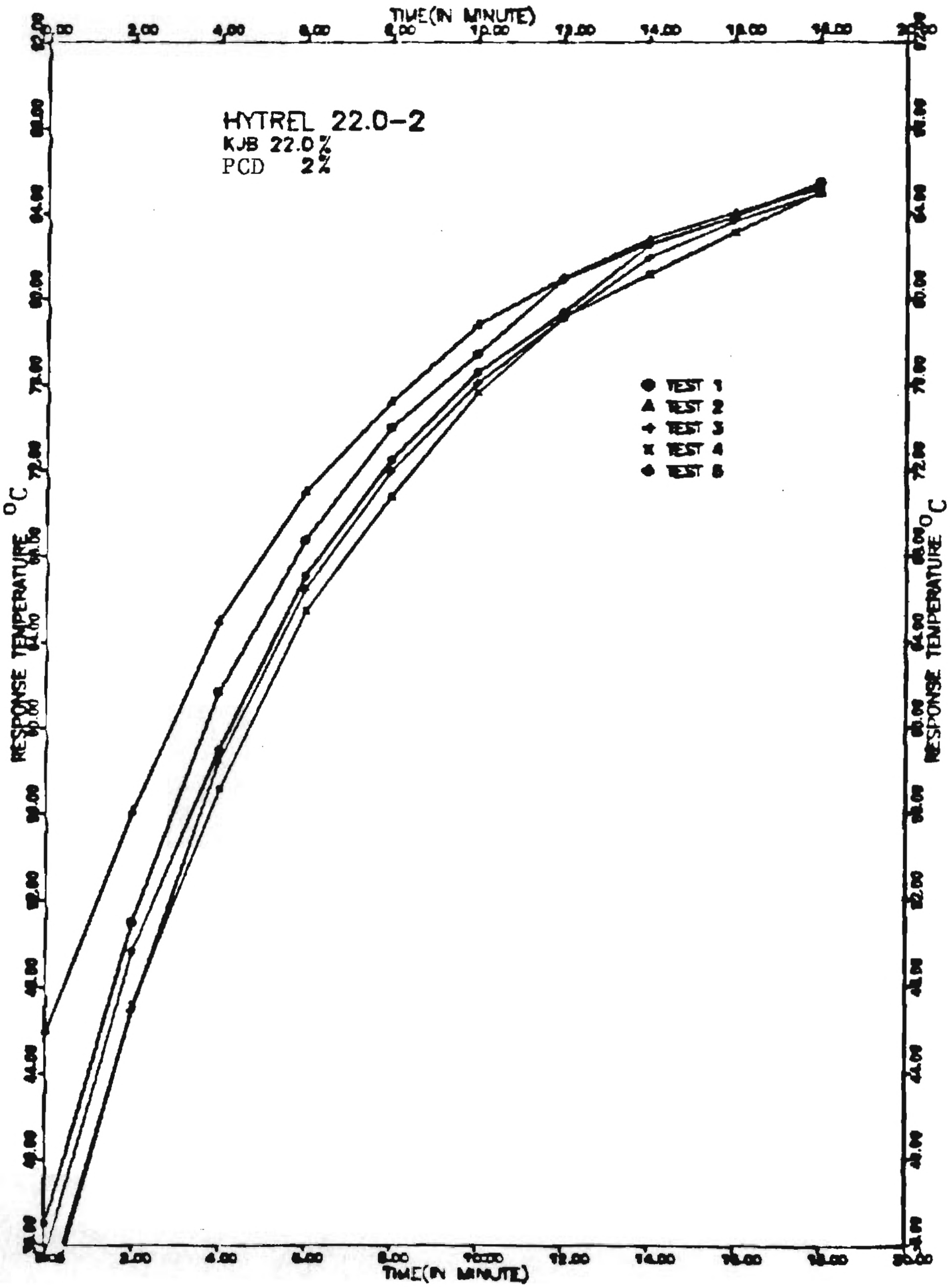


Figure 15. Time-Temperature Response for Hytrel 22-2

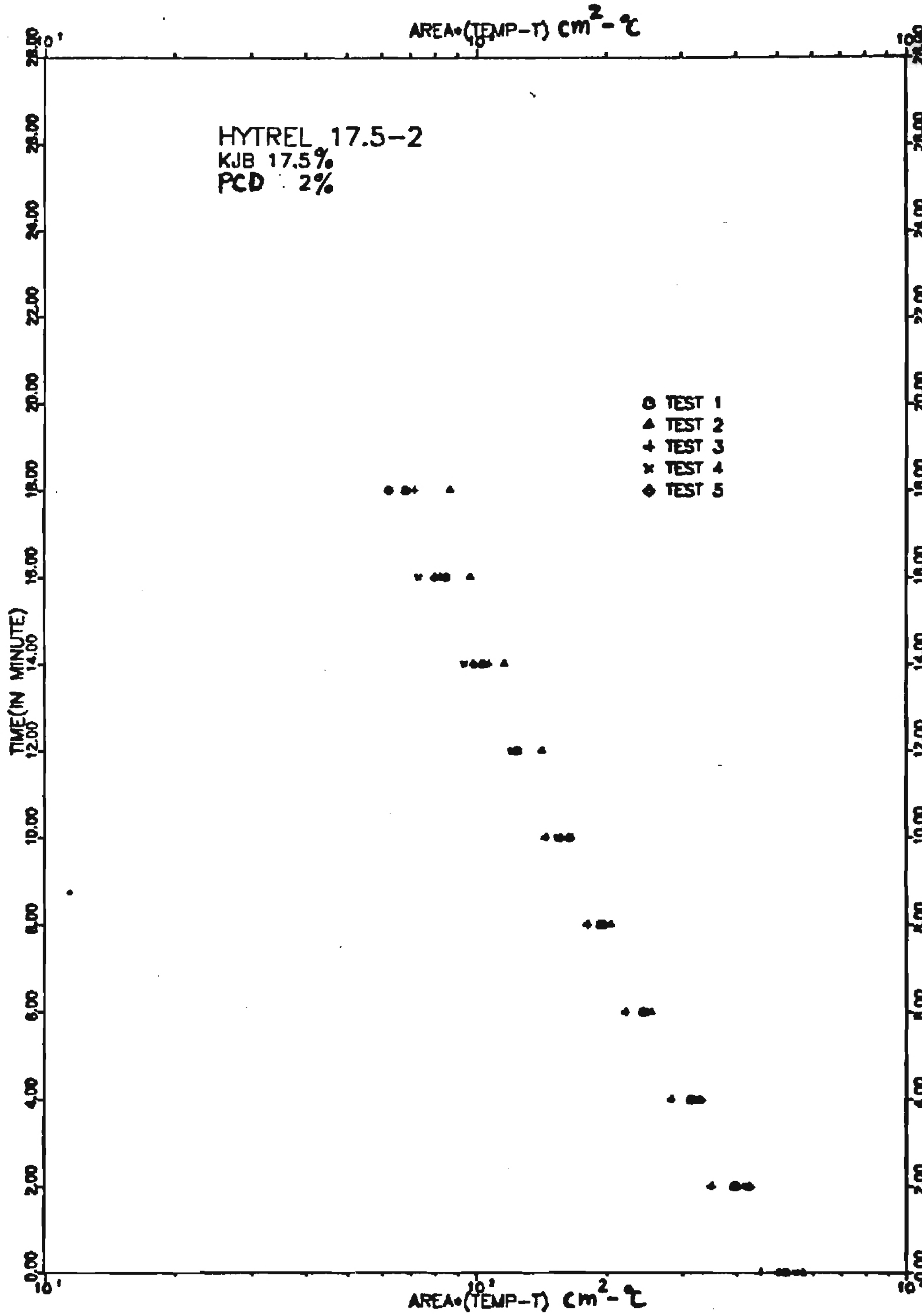


Figure 16. Time-Temperature Response in Accordance with Equation (8) for the Polyester Elastomer (Hytrel) with 17.5% Carbon and 2% Stabilizer

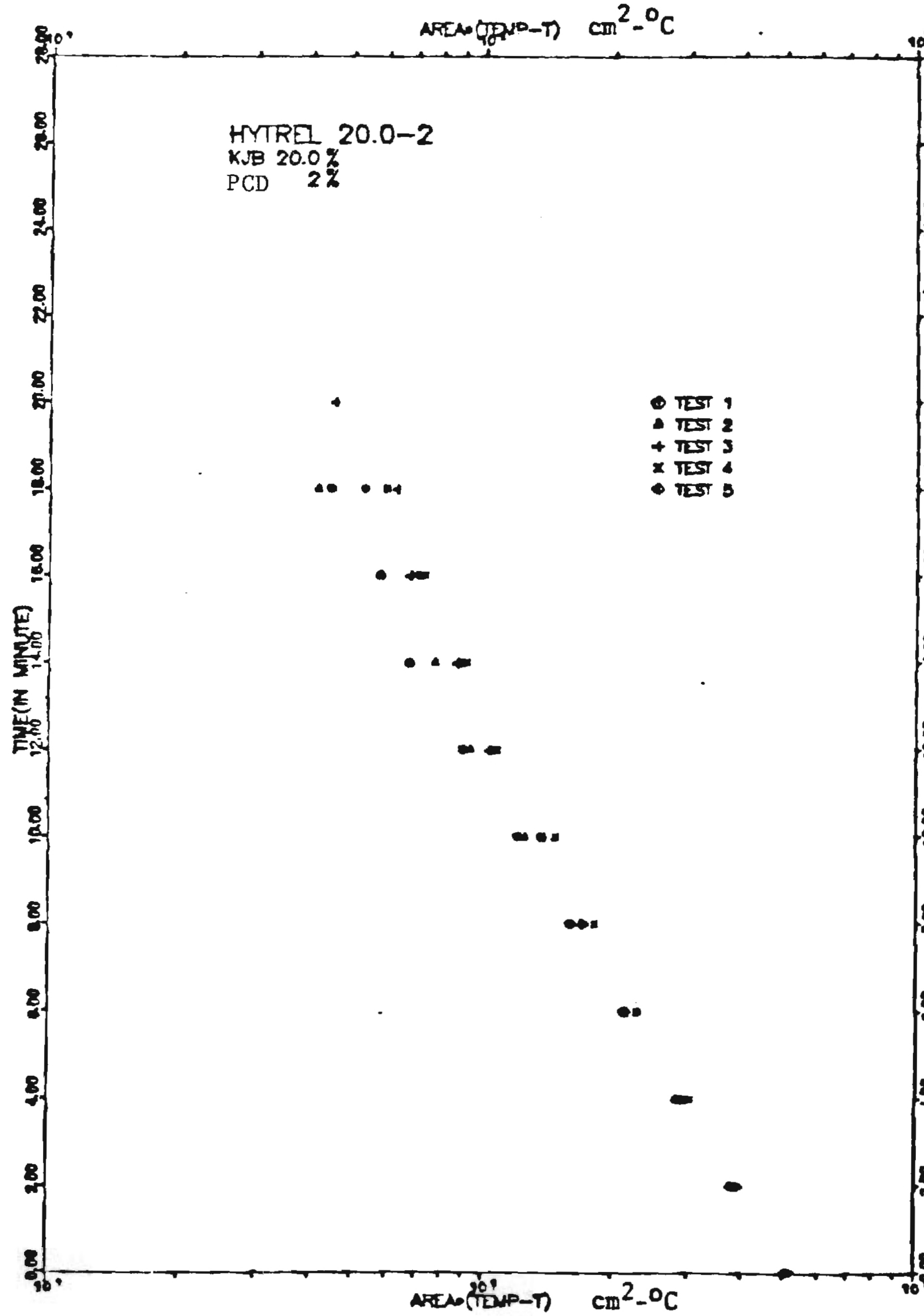


Figure 17. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 20% Carbon and 2% Stabilizer

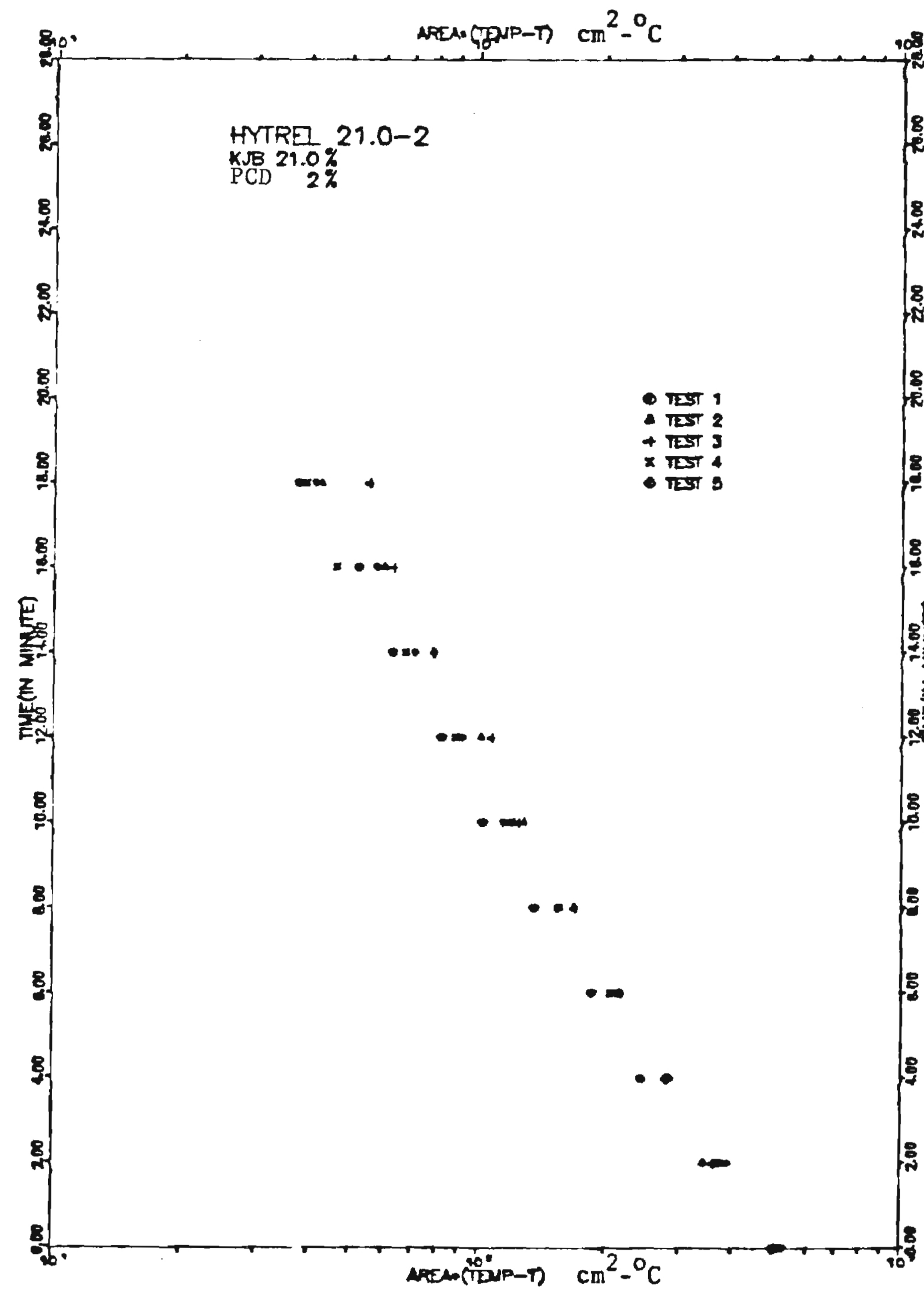


Figure 18. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 21% Carbon and 2% Stabilizer

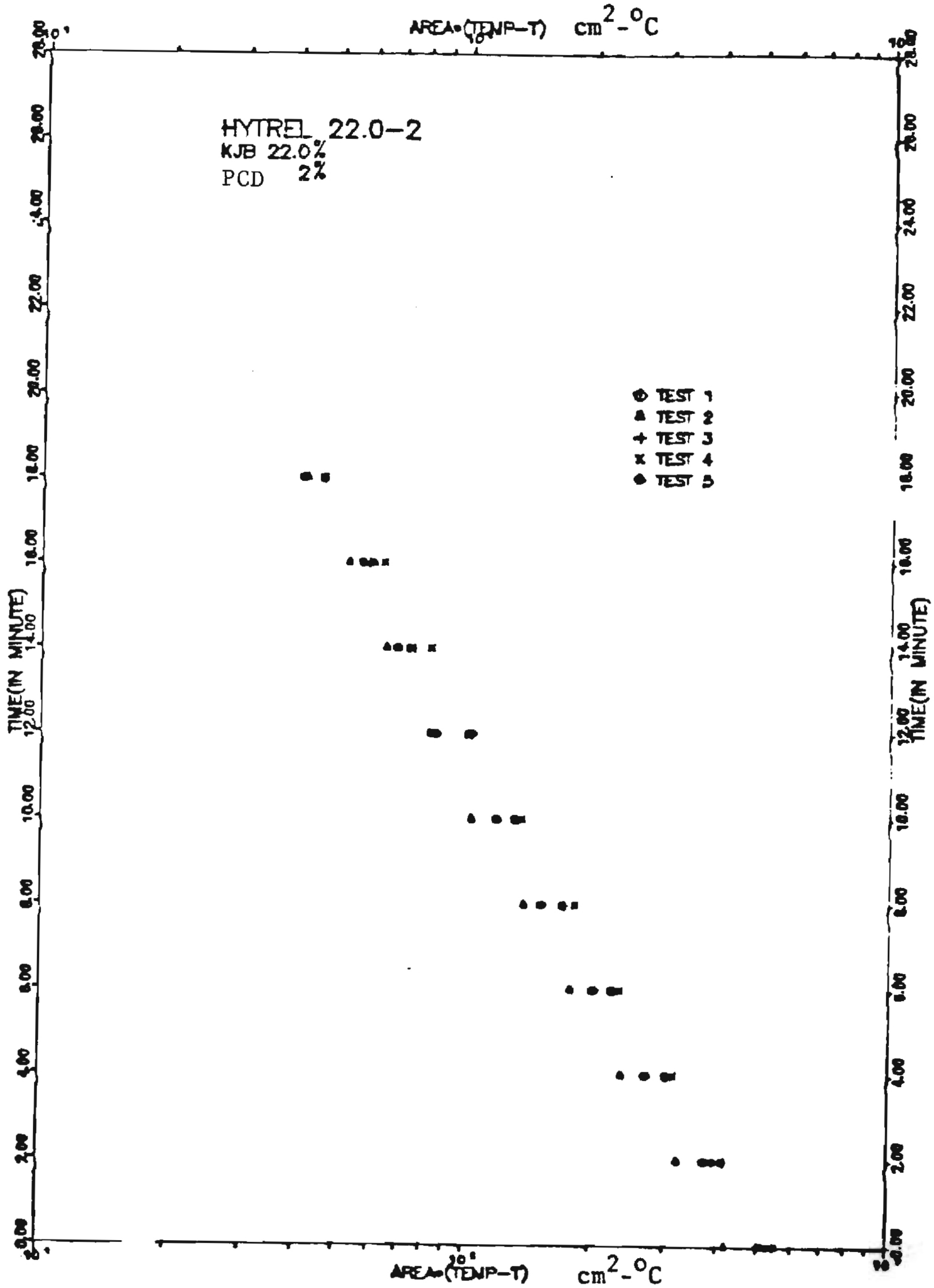


Figure 19. Time-Temperature Response in accordance with Equation (8) for Polyester Elastomer (Hytrel) with 22% Carbon and 2% Stabilizer

TABLE 14. Thermal Conductivity of Polyester Elastomer with 17.5% KJB and 2% PCD

EXPERIMENT (NO.)	Btu/hr/ft/F	THERMAL CONDUCTIVITY cal/cm/sec/deg	$kg.m./sec^3/K$
1	$2.1X10^{-1}$	$8.6X10^{-4}$	$3.6X10^{-1}$
2	$1.9X10^{-1}$	$7.7X10^{-4}$	$3.2X10^{-1}$
3	$1.9X10^{-1}$	$7.9X10^{-4}$	$3.3X10^{-1}$
4	$2.3X10^{-1}$	$9.4X10^{-4}$	$3.9X10^{-1}$
5	$2.3X10^{-1}$	$9.4X10^{-4}$	$3.9X10^{-1}$
AVERAGE	$2.1X10^{-1}$	$8.6X10^{-4}$	$3.6X10^{-1}$
STANDARD DEVIATION	$1.9X10^{-2}$	$8.1X10^{-5}$	$1.6X10^{-1}$

TABLE 15. Thermal Conductivity of Polyester Elastomer with 20% KJB and 2% PCD

EXPERIMENT (NO.)	Btu/hr/ft/F	THERMAL CONDUCTIVITY cal/cm/sec/deg	$kg.m./sec^3/K$
1	$3.1X10^{-1}$	$1.3X10^{-3}$	$5.4X10^{-1}$
2	$3.1X10^{-1}$	$1.3X10^{-3}$	$5.3X10^{-1}$
3	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.6X10^{-1}$
4	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
5	$2.8X10^{-1}$	$1.2X10^{-3}$	$4.9X10^{-1}$
AVERAGE	$2.9X10^{-1}$	$1.2X10^{-3}$	$5.0X10^{-1}$
STANDARD DEVIATION	$2.0X10^{-2}$	$1.0X10^{-4}$	$3.6X10^{-2}$

TABLE 16. Thermal Conductivity of Polyester Elastomer with 21% KJB and 2% PCD

EXPERIMENT (NO.)	Btu/hr/ft/F	THERMAL CONDUCTIVITY cal/cm/sec/deg	kg.m./sec^3/K
1	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
2	$2.5X10^{-1}$	$1.0X10^{-3}$	$4.4X10^{-1}$
3	$2.4X10^{-1}$	$9.8X10^{-4}$	$4.1X10^{-1}$
4	$2.8X10^{-1}$	$1.1X10^{-3}$	$4.8X10^{-1}$
5	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.6X10^{-1}$
AVERAGE	$2.6X10^{-1}$	$1.1X10^{-3}$	$4.5X10^{-1}$
STANDARD DEVIATION	$1.6X10^{-2}$	$6.1X10^{-5}$	$2.8X10^{-2}$

TABLE 17. Thermal Conductivity of Polyester Elastomer with 22% KJB and 2% PCD

EXPERIMENT (NO.)	THERMAL CONDUCTIVITY Btu/hr/ft/F	cal/cm/sec/deg	$kg.m./sec^3/K$
1	$2.8X10^{-1}$	$1.1X10^{-3}$	$4.8X10^{-1}$
2	$2.6X10^{-1}$	$1.1X10^{-3}$	$4.4X10^{-1}$
3	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.8X10^{-1}$
4	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
5	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
AVERAGE	$2.7X10^{-1}$	$1.1X10^{-3}$	$4.7X10^{-1}$
STANDARD DEVIATION	$7.1X10^{-3}$	0.0	$1.6X10^{-2}$

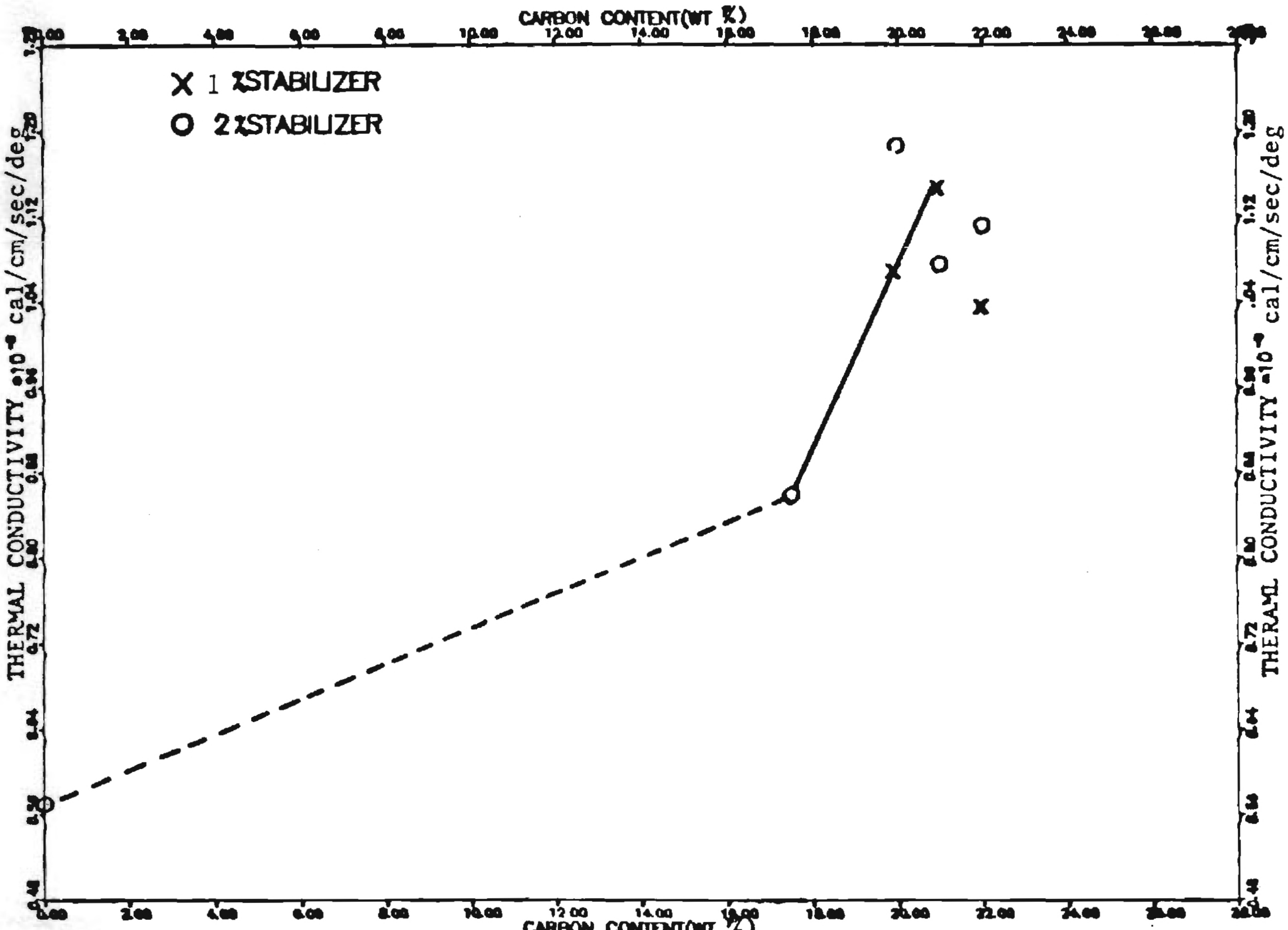


Figure 20. Thermal Conductivity of Polyester Elastomer (Hytrel) as a Function of Carbon Black (KJB) Content in Weight Percent

1.4 ELECTROCHEMICAL STABILITY

Extruded KJB graphite-filled Hytrel samples compounded in a single screw extruder were investigated for electrochemical stability in synthetic seawater. A constant applied current density was used to generate potential-time curves. The life of the electrode was taken to be the period from the onset of the test to a time when potential instability occurred. The effect of three different current densities (36 mA/cm^2, 20 mA/cm^2 and 10 mA/cm^2) on the electrode life was investigated. A chart speed of 0.01 in./min. and a full scale of 20 volts were used for this study.

The test samples were cut approximately one centimeter long and machined to obtain a cross-sectional diameter of 0.895 cm. Each test sample was manually polished with wet 240-grit paper and rinsed with distilled water. Synthetic seawater for the electrochemical tests was prepared according to ASTM standards.

The electrode was placed in a glass cell in which a platinum foil served as a counter-electrode. The cell was filled with synthetic seawater and was stirred continuously during the test. The test was performed at room temperature and in air. A potentiometer was set as a galvanostat to provide a constant current and a strip chart recorder was used to monitor the voltage on the tested samples. A schematic drawing of the equipment set-up is presented in Figure 21.

The experimental data on electrochemical life of the Hytrel base compounds for constant applied current density (10 mA/cm^2, 20 mA/cm^2, and 36 mA/cm^2) are summarized in Table 18.

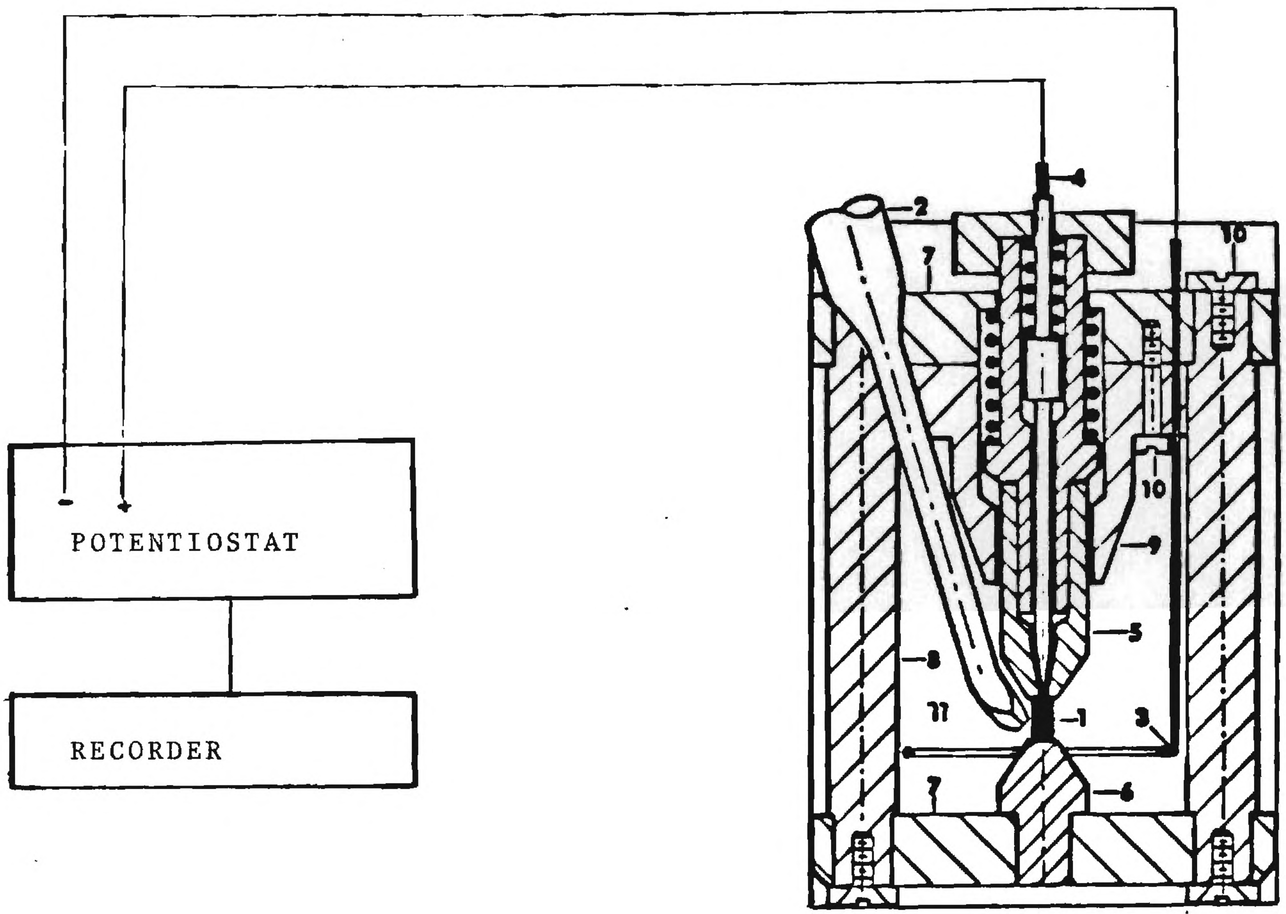


Figure 21. Experimental Setup for Applied Constant Current Electrochemical Stability Testing

1) Carbon-filled Hytrel Base Specimen
2) Glass salt bridge
3) Platinum wire counter electrode
4) Spring loaded contact
5) Spring loaded PTFE support with a metal insert
6) Lower PTFE support
7) Polycarbonate round plates
8) Polycarbonate rods
9) PTFE housing
10) Nylon bolts
11) Seawater

TABLE 18

Property Data on Conductive Hytrel Compounds - Commercial Type Mixing

Composition	Thermal Conductivity cal/cm/sec/deg	Electrical Resistivity ohm-cm	Electrical Chemical Life hrs		
			36 $\frac{mA}{Cm^2}$	20 $\frac{mA}{Cm^2}$	10 $\frac{mA}{Cm^2}$
15 - 2	9.8×10^{-4}	Good General range of 100	← No data		→
17.5 - 2	8.6×10^{-4}	50	8.5	← No data	→
20 - 1	1.1×10^{-3}	14* - 25	10.5	29	72 →
20 - 2	1.2×10^{-3}	3* - 15	17.5	32	72 →
21 - 1	1.15×10^{-3}	14* - 25	16.5	27.5	48 →
21 - 2	1.1×10^{-3}	14* - 25	16	29	48 →
22 - 1	1.04×10^{-3}	13* - 25	18	32	48 →
22 - 2	1.1×10^{-3}	5* - 20	19	31	No data

* Best value found.

In the Potentiodynamic technique, a potentiostat, a potentiometer, a scan generator, a logarithmic converter and a X-Y recorder were used to generate and simultaneously plot the potential versus applied current density curves (anodic polarization curves). The potentials were measured with respect to a saturated calomel reference electrode. A schematic diagram of the equipment is presented in Figure 22.

The potentiodynamic technique produced anodic polarization curves for the conductive polymer. These samples were investigated up to 6.0 volts (SCE) and a maximum current density of 100 mA/cm^2. To determine the anodic curves, the starting potential of 0.0 volt (SCE) was used which was then driven in the noble direction. The relationship between the polarization potential and the applied current density can be determined from these curves. Since the polarization potential is inversely related to the electrochemical stability of the electrode, a measure of electrochemical stability may be determined.

The potentiodynamic technique was employed to generate the anodic polarization curves to investigate the effect of PCD stabilizer on the electrochemical stability of the Hytrel base compounds. A summary of the Tafel Slopes for the various compounds tested potentiodynamically is given in Table 19. Figures 23, 24, 25, 26, 27 and 28 show the anodic polarization curves for the Hytrel base compounds investigated (20, 21 and 22 KJB with 1% and 2% stabilizer).

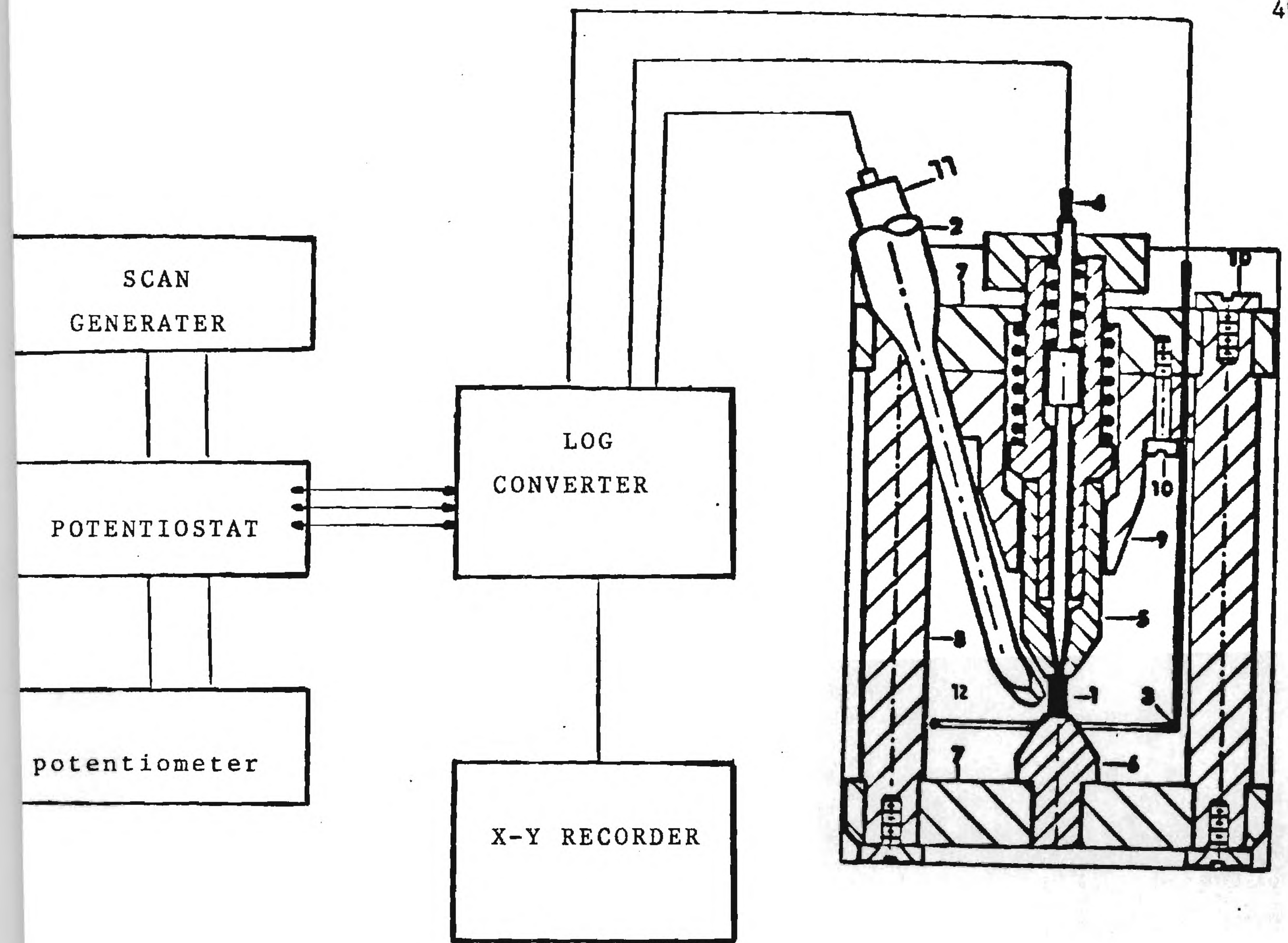


Figure 22. Experimental Setup for Potentiodynamic Scan

1) Carbon-filled Hytrel base
2) Glass salt bridge
3) Platinum wire counter electrode
4) Spring loaded contact
5) Spring loaded PTFE support with a metal insert
6) Lower PTFE support
7) Polycarbonate round plates
8) Polycarbonate rods (3)
9) PTFE housing
10) Nylon bolts
11) Calomel Reference Electrode
12) Seawater

Table 19

Tafel Slopes for Compounds Tested

Sample	Tafel Slope (V/dec)
20-1	2.9
20-2	2.2
21-1	5.0
21-2	2.2
22-1	2.4
22-2	1.7

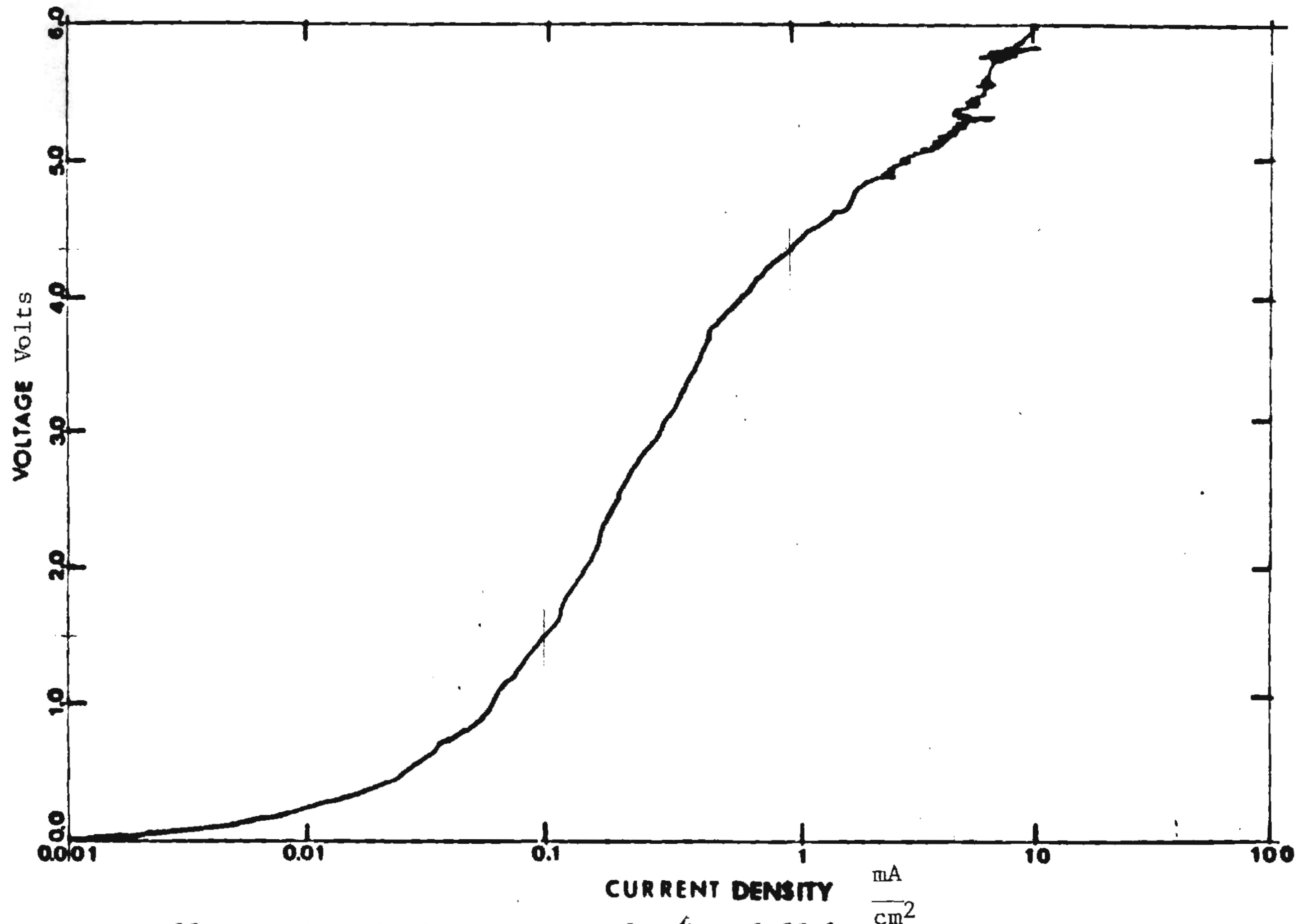


Figure 23. Anodic Polarization Curve for Hytrel 20-1

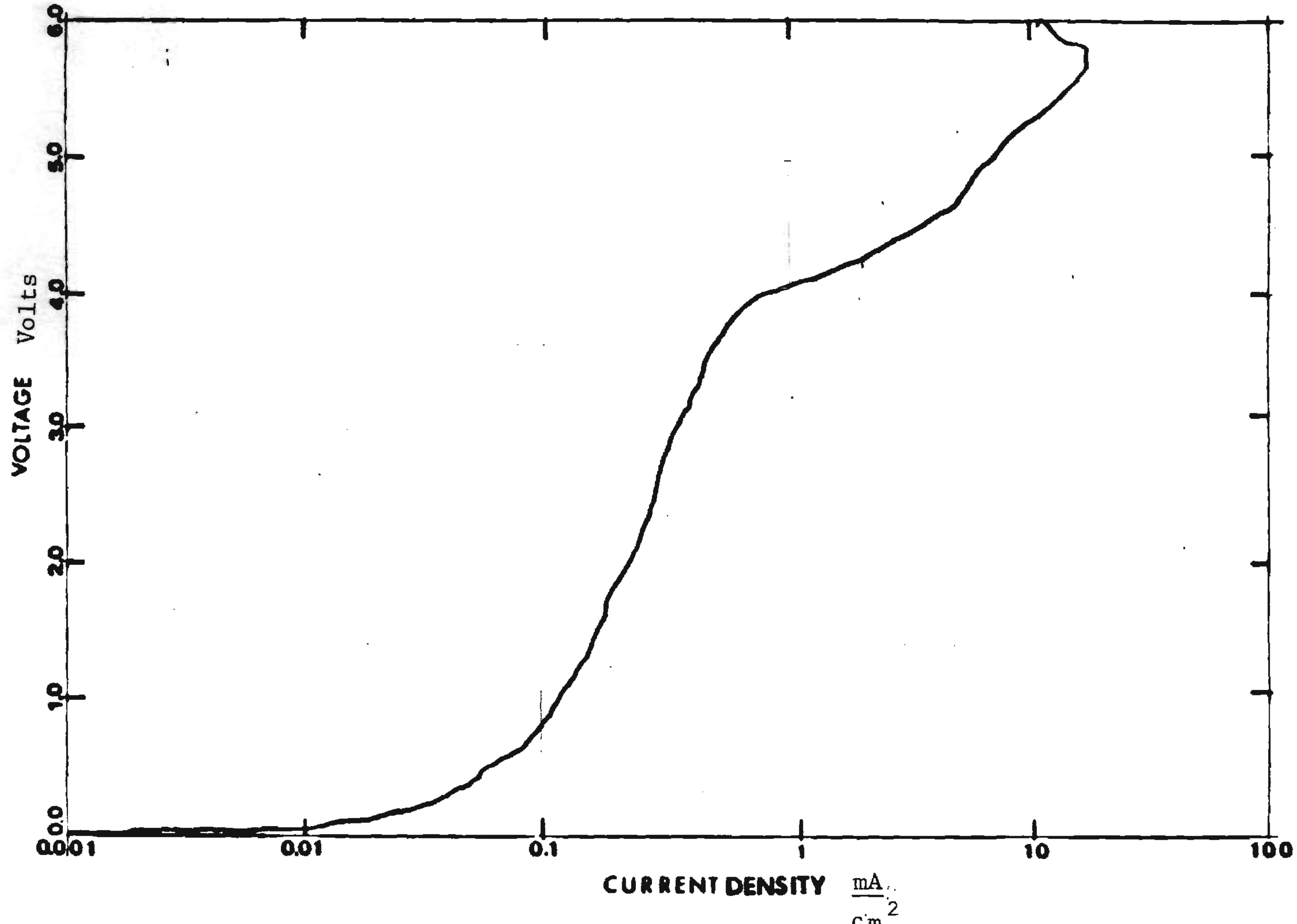


Figure 24. Anodic Polarization Curve for Hytrel 21-1

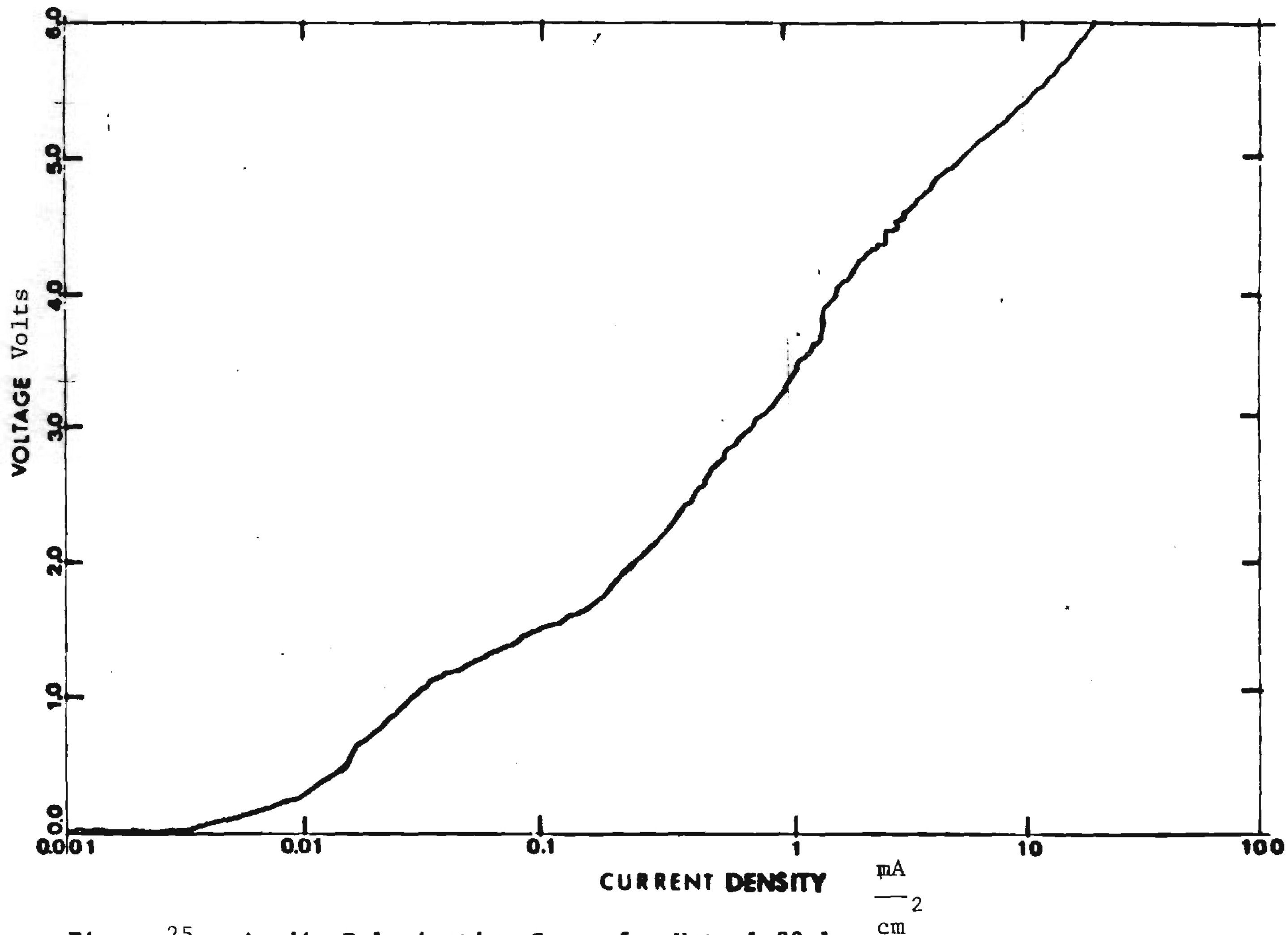


Figure 25. Anodic Polarization Curve for Hytrel 22-1

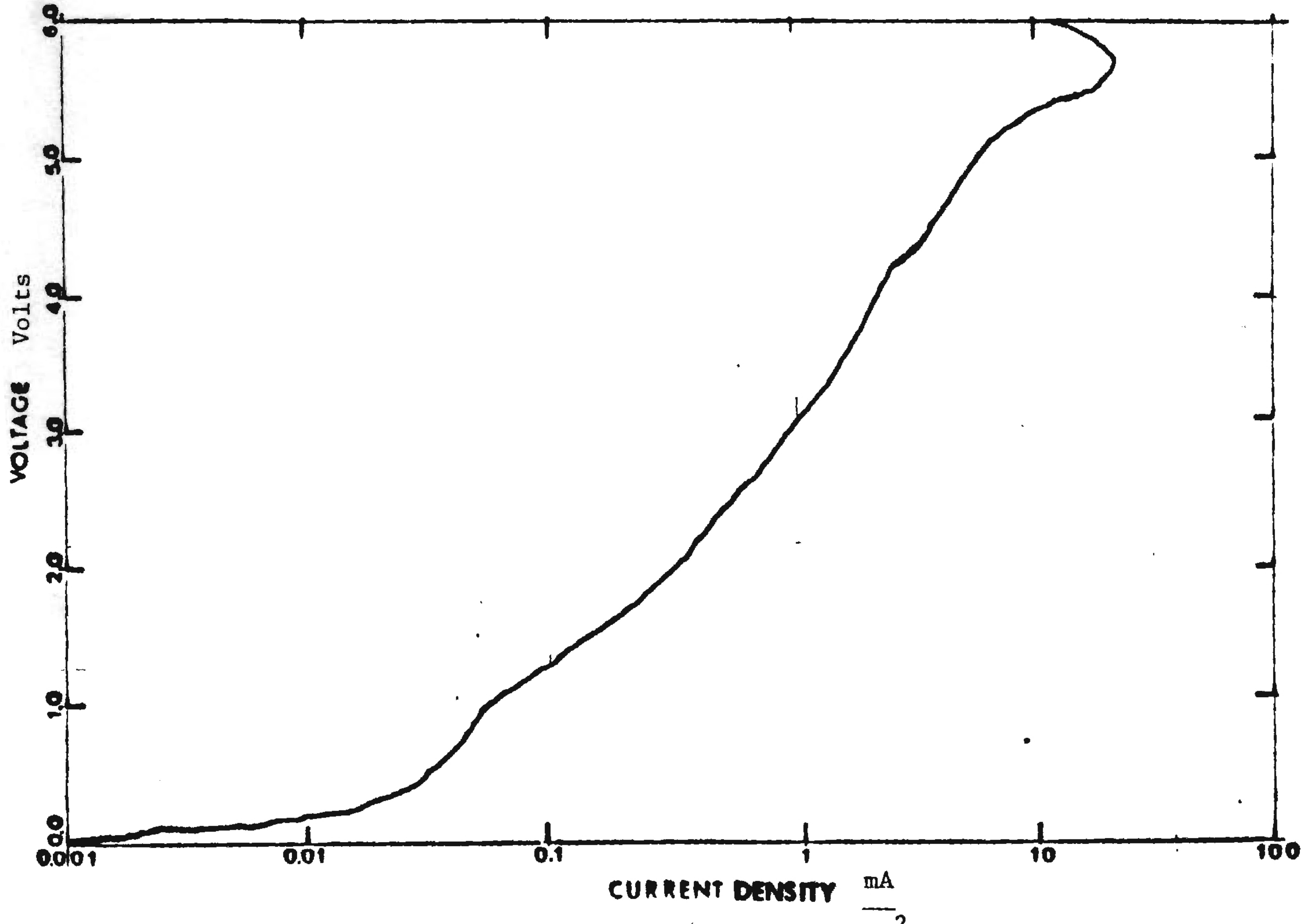


Figure 26. Anodic Polarization Curve for Hytrel 20-2

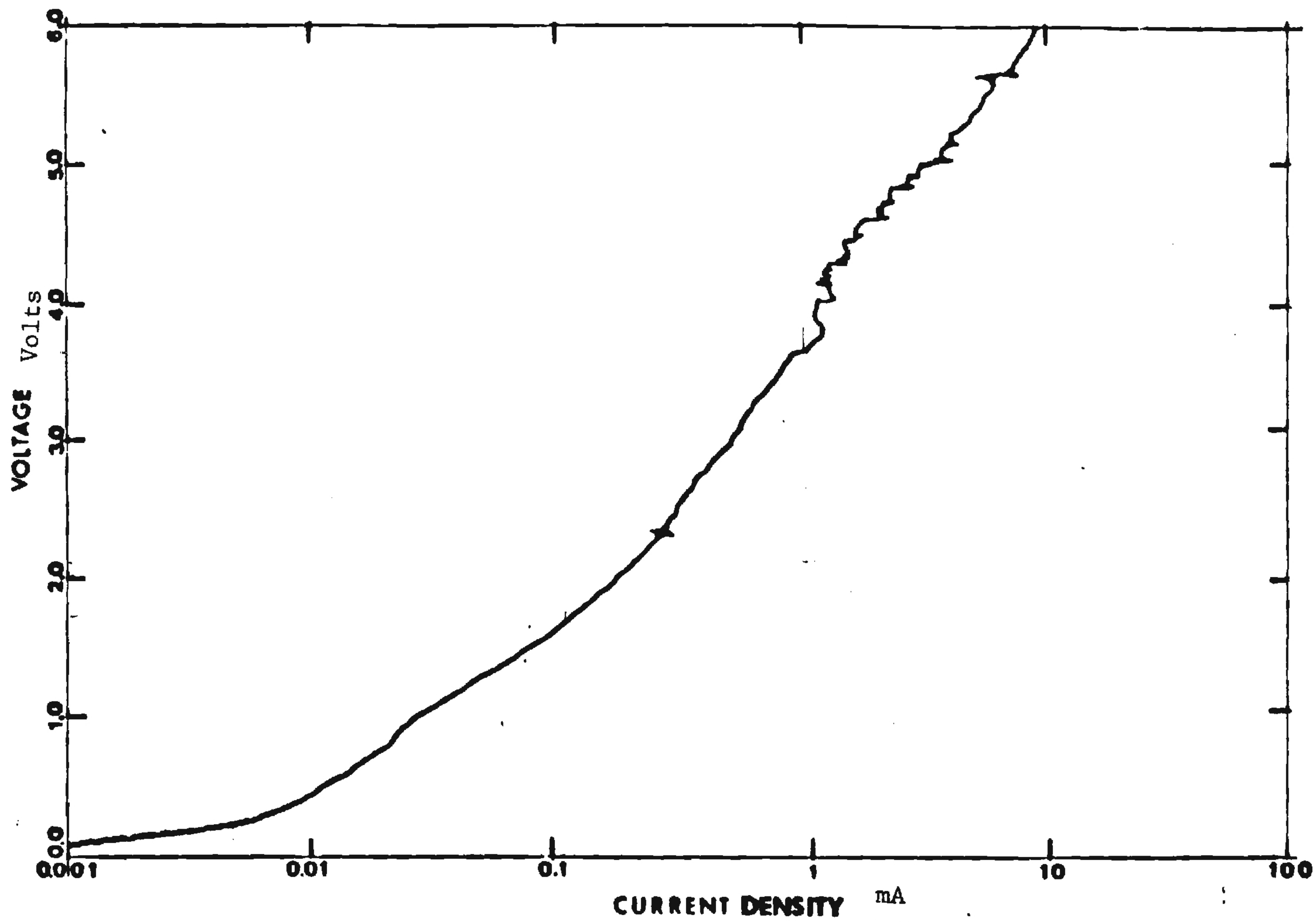


Figure 27. Anodic Polarization Curve for Hytrel 21-2

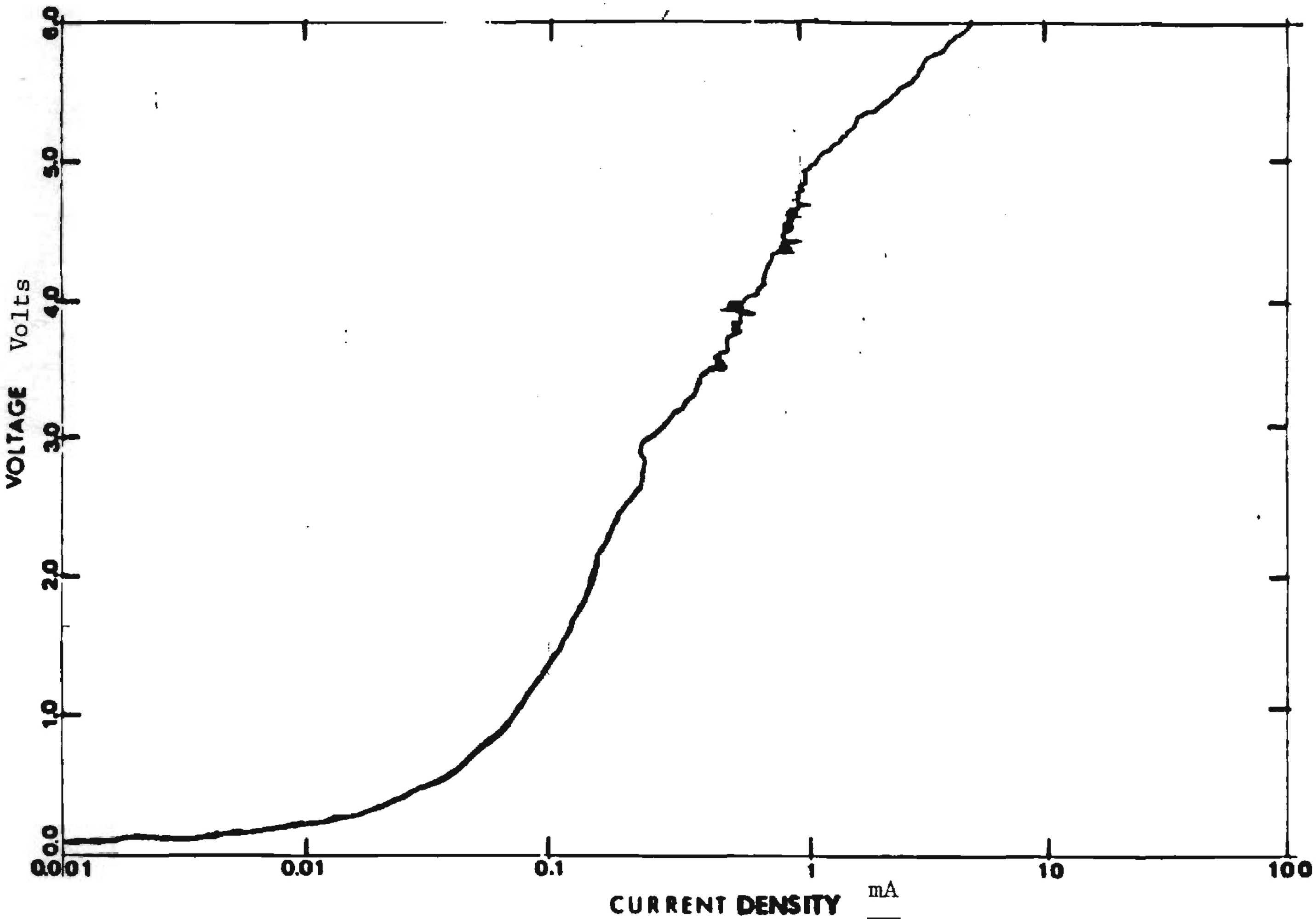


Figure 28. **Anodic Polarization curve for Hytrel 22-2**

1.5 TENSILE PROPERTIES OF CARBON-FILLED STABILIZED HYTREL COMPOUNDS

In all the studies each compounded material was checked initially in a general way by comparing its flexibility and abrasion resistance to pure Hytrel. However, a mold was prepared which could produce a uniform tensile sample from the single screw extruder, which could be used to measure quantitatively the modulus, the strength and the plasticity. A series of 20-1, 20-2, 21-1, 21-2, 22-1 and 22-2 samples were prepared and tested in an Imstron universal tester. The results of these tests are given in Appendix I and are summarized in Table 20 below.

TABLE 20

Sample	Av. Ultimate Strength	Av. % Elong.	Young's Modulus
20-1	2,940 psi unbroken	420% + unbroken	21,200 psi
20-2	3,070 psi unbroken	410% + unbroken	25,600 psi
21-1	2,710 psi	350%	22,500 psi
21-2	2,490 psi	340%	28,500 psi
22-1	2,560 psi	350%	23,900 psi
22-2	2,810 psi	325%	22,500 psi

1.6 DISCUSSION OF RESULTS

The following sections will discuss each property of the optimized KJB-stabilized Hytrel compounds in terms of the data on their applicability to a conductive electrode jacket. This discussion forms the basis of the final conclusions and recommendations.

1.6.1 ELECTRICAL RESISTIVITY

The effect of increasing the carbon content on the electrical resistivity of the carbon-filled polymer compounds shows the best electrical conductivity of the stabilized Hytrel-graphite combinations in the range from 20% to 22% by weight. Lower carbon compositions were investigated earlier but were found to be decidedly lower in electrical conductivity. The electrical resistivity of the compounded polymers produced from the single screw extrusion mixing process showed good electrical conductivity in the 3 to 15Ω-cm range. The test results have shown that the KJB carbon is the primary medium in the polymer matrix for electron conduction. The KJB carbon produces conductivity in the Hytrel base matrix by creating conductive paths through which current can flow. The 20% KJB level may represent conductivity near the maximum for an effective material and raising the carbon content above 20% has very little effect on decreasing the electrical resistivity, but does decrease the mechanical properties.

To study the effect of increasing the hydrolytic stabilizer level on electrical resistivity of the conductive polymer, the electrical resistivity of the Hytrel base compound was plotted as a function of KJB content for 1% and 2% MS stabilizer (see Figure 1). The test results showed that the stabilizer affected the electrical resistivity of Hytrel-carbon combinations by decreasing the specific resistance to a lower value depending on the stabilizer content. The Hytrel base compounds containing 1% stabilizer had electrical resistivity consistently near 12 to 15 ohm-cm. At 2% stabilized, the specific resistance decreased to around 5.0 ohm-cm. Because of the hygroscopic nature particularly of the Hytrel polymer, moisture absorbed during processing tends to interlock with the matrix and the carbon particles. It is believed that hydrolytic stabilizer reduces the absorbed moisture resulting in an electrically more conductive compound for the higher stabilizer level.

The effect of varying current density on the electrical resistivity was also studied. Within the range of 0.024 mA/cm^2 to 0.24 mA/cm^2 the electrical resistivity was independent of the current density.

1.6.2 THERMAL CONDUCTIVITY

The effect of increasing the KJB carbon level on the thermal conductivity of the conductive polymer compound was investigated for Hytrel-graphite combinations with 1% and 2% Hytrel PCD stabilizer by weight. The thermal conductivity of the compounded Hytrel at various carbon levels ranging from 17.5% to 22% KJB carbon indicated that KJB carbon, besides aiding electrical conductivity, is also an aid to the thermal conductivity. The effectiveness of this thermal conductivity depends on uniformly distributed KJB carbon in the base polymer matrix. This effect of the KJB carbon on improving the thermal conductivity of the Hytrel-KJB compound was most notable at carbon compositions ranging from 17.5% to 20% KJB content by weight. For Hytrel compounded with carbon equal to or above 20% KJB, nearly a 100% increase over pure Hytrel is realized. KJB contents above 20% by weight have little effect on further increases in the thermal conductivity.

The effect of hydrolytic stabilizer on the thermal conductivity of the conductive Hytrel base compound was investigated for Hytrel-graphite combinations compounded with 1% and 2% stabilizer. Comparison of the test results showed a slightly higher thermal conductivity for a Hytrel-graphite compound containing 2% PCD than for the same Hytrel-graphite compound with only 1% stabilizer.

Some carbon-filled Hytrel compounds produced in batch mixing processes gave an inconsistent time-temperature response history. One sample produced from the batch mixing process containing 15% KJB graphite by weight was found to be more thermally conductive than a compound containing 20% KJB graphite. The reasons for this abnormality was the carbonization of the Hytrel base at temperatures above 200° C, thereby providing more carbon in the base material for thermal conduction. At temperatures lower than 190°C, good mixing is not realized and at temperatures above 200°C, carbonization of the Hytrel base, although it may increase the conductive properties, results in degradation of the mechanical properties of the compound.

1.6.3 ELECTROCHEMICAL LIFE

It is important to remember in the evaluation of these polymers, two things are different in these particular polymers than in the previous studies that showed lives in excess of 50 hours (one result as high as 70 hours) at 20 $\frac{mA}{cm^2}$. Differences in the fabrication techniques due to use of industrial equipment resulted in stabilizer being lost due to heating above the satisfactory or good fabrication temperature range for Hytrel and the stabilizer. Some carbonization of the Hytrel was occurring. Add to this that the electrochemical tests were also done in a more critical manner.

Specimens were put under a load to better simulate potential loading effects upon the material, and indeed this may be more stringent than electrochemical testing should be. The true results will only be well defined when the three tubular type sections being prepared for NCSC are tested.

The electrochemical life was determined by using two constant current density tests at 10 $\frac{mA}{cm^2}$, 20 $\frac{mA}{cm^2}$ and 36 $\frac{mA}{cm^2}$and these are summarized in Table 18. This table also provides information with regard to the types of samples tested and the relative amount of carbon and stabilizer used in each sample. At this time the mechanism of deterioration of the carbon filled polymer is not precisely known although one facet of the problem we do know, that is oxidation of the carbon to carbon dioxide plus the potential for formation of carbonates. It appears that loss of stabilizer due to the slightly excessive heating in commercial type processing has resulted in a decrease in electrochemical life. The stabilizer generally slows the reaction with moisture. Data on variations in potential and current for some of the shorter-lived materials also indicated that some non-uniformity of mixing can occur to some extent in commercial processing compared to hand processing in the lab.

A second series of corrosion tests consisted of anodic polarization. Tafel slopes from the anodic polarization curves were determined and a study of this data vs. life was performed. Lower Tafel slopes are more favorable because a higher current density is reached at a lower voltage; at lower voltages the electrochemical deterioration is less rapid. In this respect sample 22-2 showed the lowest slope at the current density above 1.0 mA/cm^2. All samples, however, showed similar very high voltages needed to achieve current density in the design range.

The values in Table 19 are about an order of magnitude higher than Tafel slopes for common electrochemical reactions, including those reported for solid carbon electrodes. The published data, however, were obtained for potentials below 2 V and low current densities. In the carbon-filled polymer the true current density on the carbon is higher than the nominal current density shown in the graphs, because carbon covers only a fraction of the surface area. The high true current density, and the steepness of the slopes at higher current densities results in relatively high voltage at the design current density and consequently relatively rapid deterioration. Slowing down the rate of deterioration seems to require both an improved stability of the polymer and an electrochemically more effective form of carbon.

1.6.4 MECHANICAL PROPERTIES

In a preliminary evaluation, all samples were tested semiquantitatively for flexibility and abrasion resistance. The materials when properly compounded in the 17.5% to 22% KJB and 1% to 2% stabilizer range showed mechanical properties satisfactory for the jacket material. However, compounds with 4% or more stabilizer showed a marked embrittlement and hence were unsatisfactory for the application.

Tensile tests were made to evaluate the materials with the most overall promise. The results indicate that for 20% KJB and 1% or 2% stabilizer, the overall strength, plasticity and modulus are most satisfactory. There are indications of slight losses in the best combination of mechanical properties as KJB and stabilizer are increased. It is apparent that 2% to 2.5% stabilizer and 22% KJB carbon may be the maximum allowable percentages to maintain effective mechanical properties for a Hytrel 4056 base, particularly in light of the effect of the electrochemical reaction on the system.

CHAPTER II

ELECTRODE SYSTEM ANALYSIS

2.1 Initial Analysis

The following initial results are from a computer simulation of an example minesweeping system using conducting jacket anode and cathode. Table 2-I is a list of parameter values for the electrodes. Using an electrode length of 110 meters, Figure 2-1 and Figure 2-2 show the temperature and resistance as a function of aluminum area. Figure 2-1 shows that at least 3.3 million circular mills of conductor area is needed to keep the hottest temperature of both the anode and cathode under 100 degrees celsius. Figure 2-3 shows that the change in temperature is minimal as the conductor length is varied. This is a general result for all electrodes studied. Figure 2-4 shows that a conductor length of at least 110 meters is needed to keep the total resistance under 15 milliohms. It has been found that electrode length is the key parameter in the determination of electrode system resistance. Figure 2-5 and 2-6 show the temperature and resistance of 4 different jacket thicknesses as the jacket electrical conductivity is varied while the conductor area and conductor length were fixed at 3.3 million circular mills and 110 meters respectively. The figures show that a jacket electrical conductivity greater than 0.5 mho/meter is desired and little improvement is obtained for higher conductivities. Figure 2-7 and 2-8 show the temperature and resistance for 4 different jacket thicknesses as the jacket thermal conductivity is varied while the conductor area and length are fixed at 3.3 million circular mills and 110 meters, respectively. It can be seen that a jacket thermal conductivity greater than about

TABLE 2-I. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	10.541 cm (4.150 inches)
Length	110 meters (360.9 ft)
Maximum Current	$\geq$8500 amperes
Maximum Temperature	$\leq$100.0°C
Maximum System Resistance	$\leq$15.0 milliohm
Bending Radius	$\leq$3 feet
Core	
Material(s)	Heat resistant ABS and Silicone Foam
Diameter	8.260 cm (3.252 inches)
Thermal Conductivity	$\geq 7.53 \times 10^{-4}$ W/cm°C
Electrical Conductivity	$\leq 10^{-5}$ mho/m
Specific Gravity	$\leq$0.3
Core Sheath	
Material	4" Mylar Tape 4 mills thick with 45% overlap
Thickness	6 mills
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	$\leq 10^{-5}$ mho/m
Specific Gravity	$\leq$1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	$\geq$2.36 W/cm°C
Electrical Conductivity	$\geq 3.536 \times 10^{7}$ mho/m
Thermal Coefficient	$\leq$0.56%/C
Specific Gravity	$\leq$2.7
Number of Conductors	56
Winding Pitch Angle	21.7°
Shape of Conductors	Round
Size of Conductors	29,464 CM
Percent Fill of Aluminum	74.9
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	$\leq$1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 4 mills thick with 45% overla
Thickness	6 mills
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	$\geq$.5 mho/m
Specific Gravity	$\leq$1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	≥ 2.36 W/cm°C
Electrical Conductivity	$\geq 3.536 \times 10^{7}$ mho/m
Thermal Coefficient	$\leq 0.56\%/C$
Specific Gravity	≥ 2.7
Number of Conductors	67
Winding Pitch Angle	21.7
Shape of Conductors	Round
Size of Conductors	24,627 CM
Percent Fill of Aluminum	74.6
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	≤ 1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 4 mills thick with 45% overlap
Thickness	6 mills
Thermal Conductivity	$\geq 2.95 \times 10^{-3}$ W/cm°C
Electrical Conductivity	≥ 0.5 mho/m
Specific Gravity	≤ 1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	$>2.8 \times 10^{-3}$ W/cm°C
Electrical Conductivity	>0.5 mho/m
Specific Gravity	≤ 1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30°C
Thermal Conductivity	5.796×10^{-3} W/cm°C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

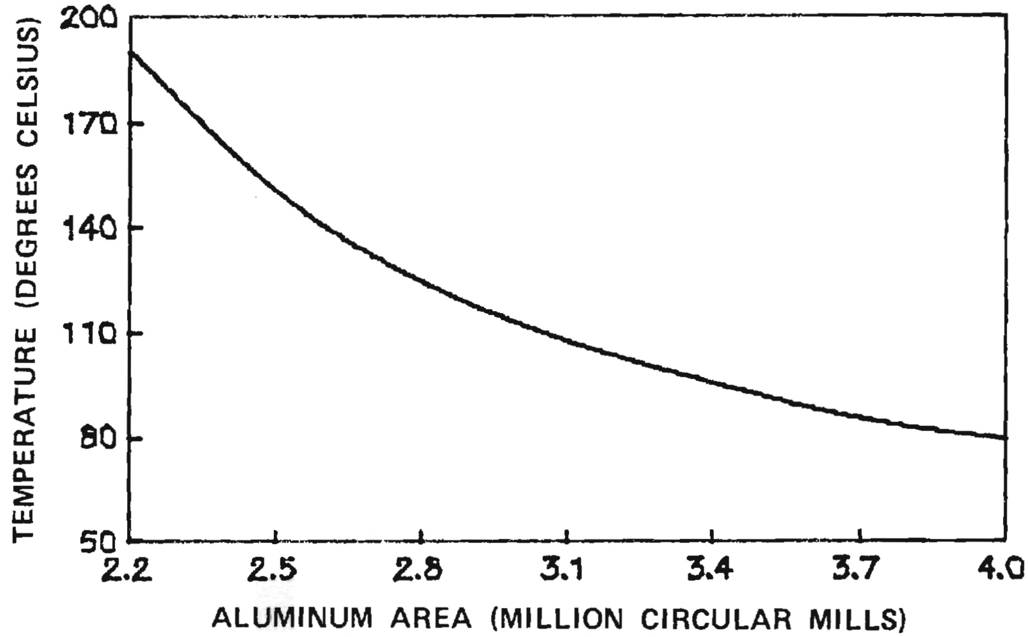


Figure 2-1. **Electrode Temperature Versus Conductor Size**

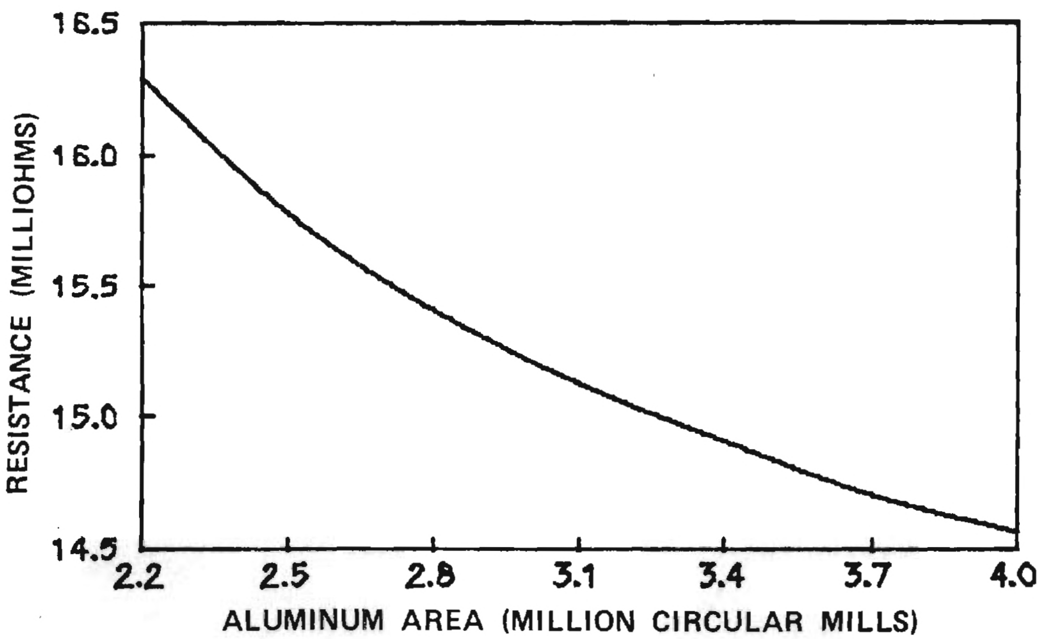


Figure 2-2. **System Resistance Versus Electrode Conductor Size**

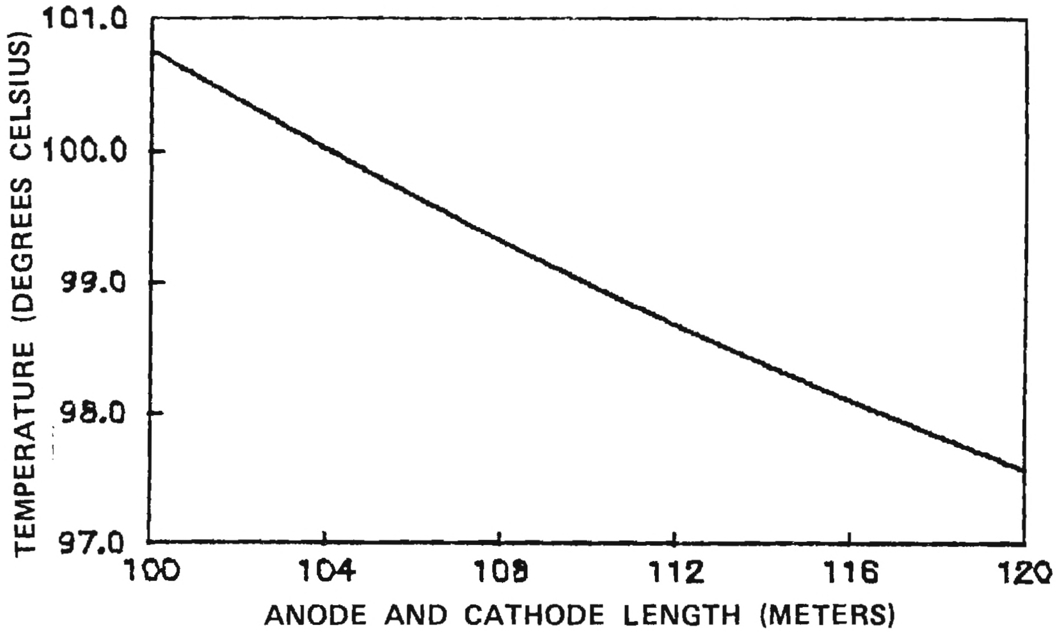


Figure 2-3. **Electrode Temperature Versus Electrode Lengths**

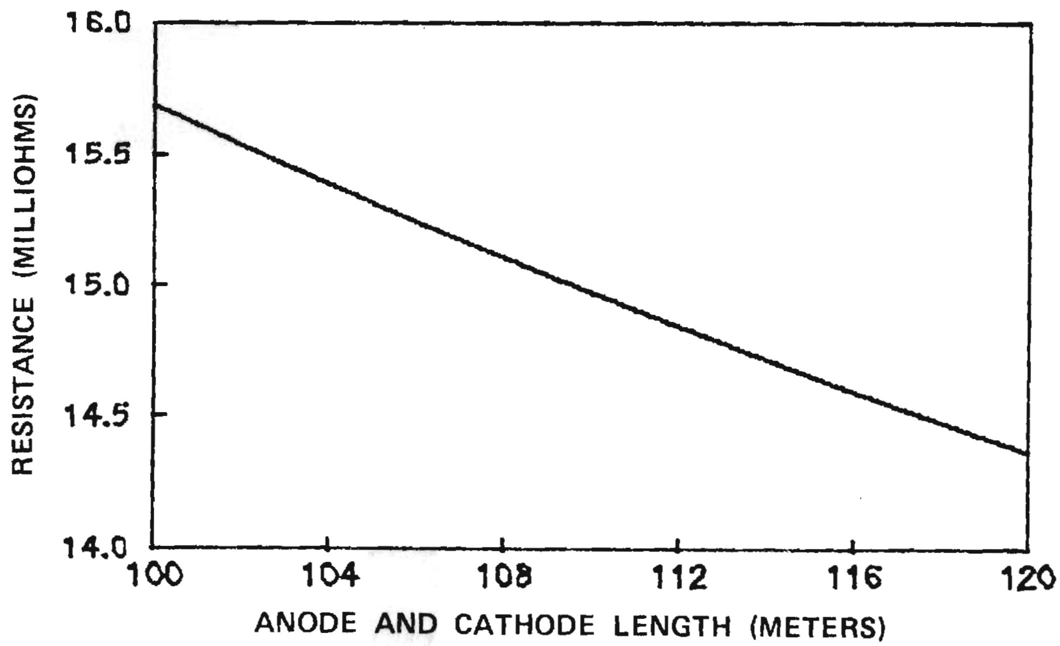


Figure 2-4. **System Resistance Versus Electrode Lengths**

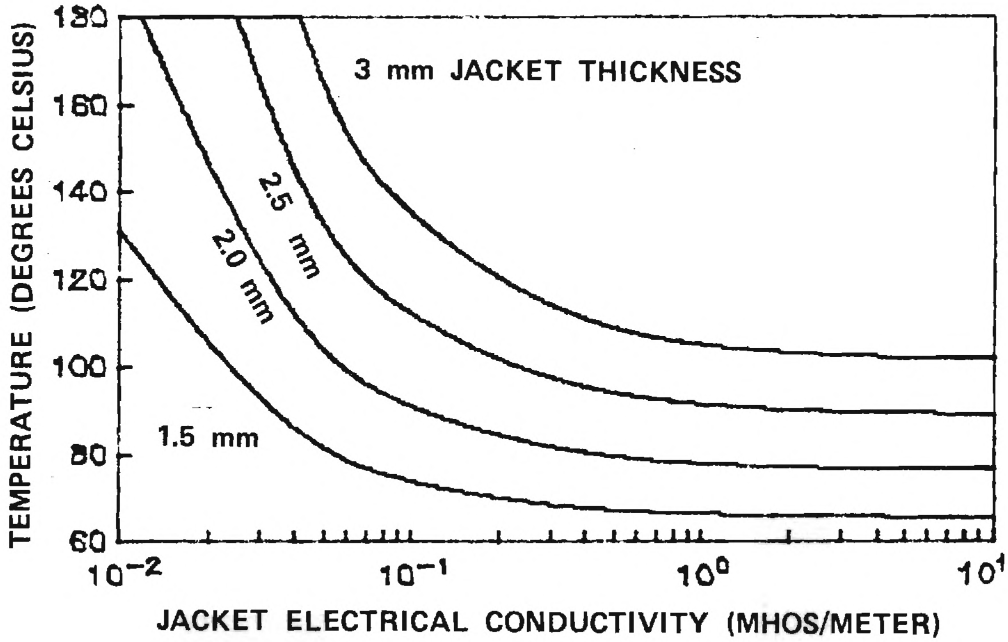


Figure 2-5. **Electrode Temperature Versus Electrode Jacket Electrical Conductivity**

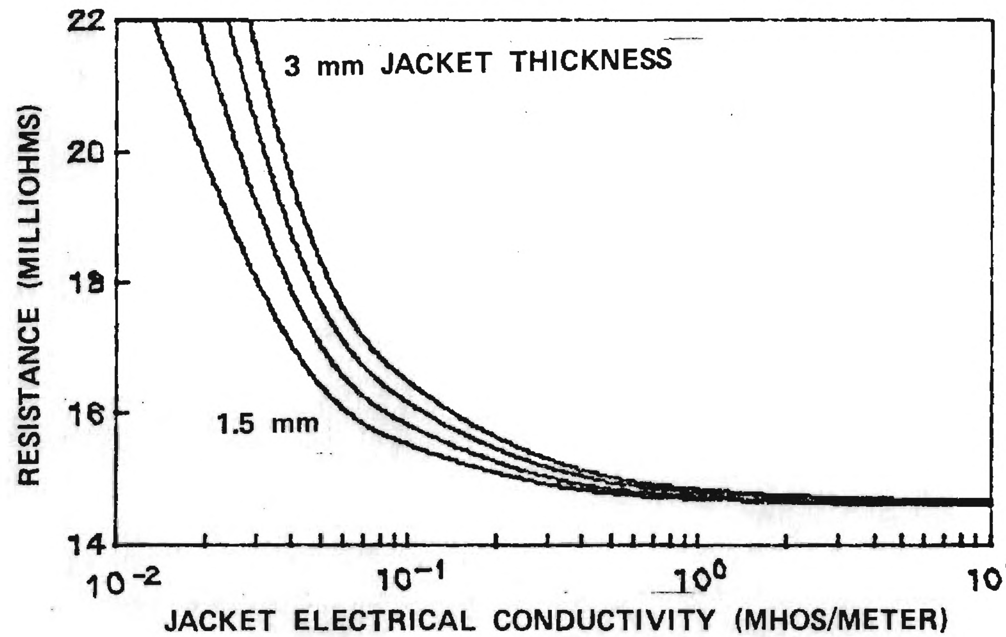


Figure 2-6. **System Resistance Versus Electrode Jacket Electrical Conductivity**

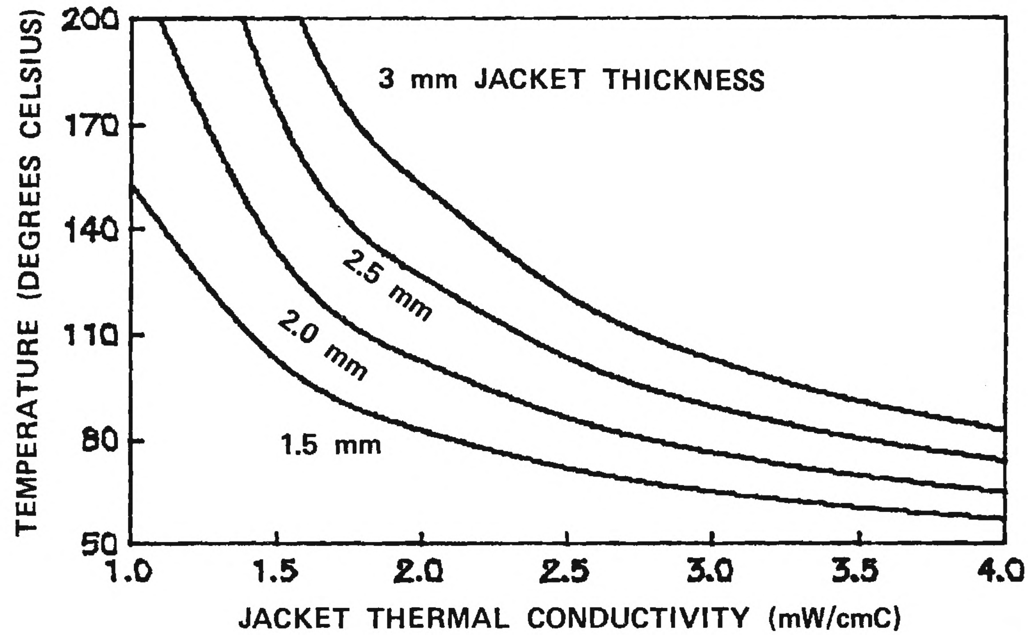


Figure 2-7. **Electrode Temperature Versus Electrode Jacket Thermal Conductivity**

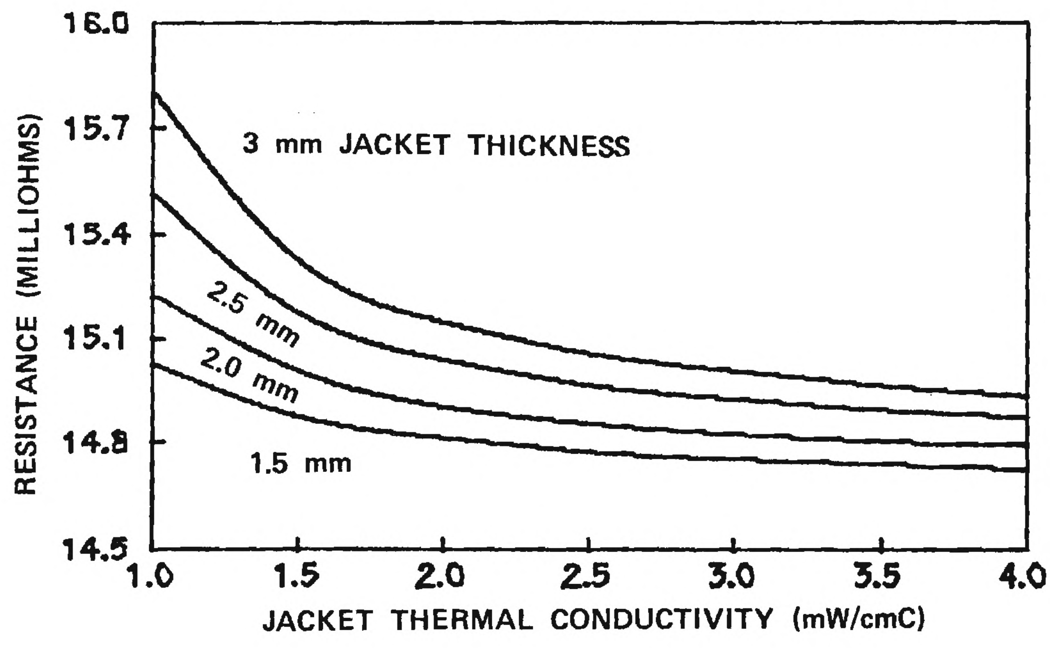


Figure 2-8. **Electrode Temperature Versus Electrode Jacket Thermal Conductivity**

2.8 milliwatt/cmC^{o} is desired to keep the temperature lower than 100^{o}C and the resistance lower than 15mΩ for the given range of jacket thicknesses. These figures show that further increases in jacket thermal conductivity will reduce electrode temperature and thus allow the design of smaller diameter electrodes.

2.2 High Thermal Conductivity Jacket Material Simulations

Several modifications of the electrode materials and construction result in improved electrode system performance. Some modifications were slight such as a reduction in the mylar sheath thicknesses from 4 mills thick with 45% overlap to 2 mills thick with 45% overlap resulted in lowering the electrode temperature several degrees celsius. Other modifications such as the use of the high thermal conductivity jacket material are shown to have large impact on electrode diameter and stiffness. Table 2-II and Figure 2-9 show the electrode parameter values and radial current densities along the anode and cathode electrodes respectively using standard Hytrel jacket material with thermal conductivity of 2.8×10^{-3} W/cm C^{o}. The diameter of the electrodes is 10.5 cm, length of each electrode is 110 m, the total aluminum cross section is 3.3 million circular mils, and the stiffness is 7.52×10^{4} lb/in^{2}. Table 2-III and Figure 2-10 show the electrode parameter values and radial current densities respectively using the high thermal conductivity jacket material. This material has a thermal conductivity of 4.23×10^{-3} W/cm C^{o}, an increase of 51%. The electrodes have been reconfigured to keep the temperature below 100^{o}C at operating current. The diameter is reduced 9.12% to 9.23 cm and the total amount of aluminum conductor is reduced by 24.2% to 2.5 million circular mils. The length of the electrodes increased, however, 7.3% to 118 m to keep the total system resistance under

15 milliohms. The drag is reduced by 6% and the stiffness is reduced by 60 percent to 4.48×10^4 lb/in^2.

Average current densities are increased by 6% to a value near 25 ma/cm^2, however, peak current density increased from 39 ma/cm^2 to 47 ma/cm^2.

TABLE 2-II. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	10.500 cm (4.134 inches)
Length	110 meters (360.9 ft)
Maximum Current	8500 amperes
Maximum Temperature	100.0°C
Maximum System Resistance	15.0 milliohm
Bending Radius	3 feet
Stiffness	7.52×10^4 lb/in^2
Core	
Material(s)	Heat resistance ABS and Silicon Foam
Diameter	8.244 cm (3.246 inches)
Thermal Conductivity	7.53×10^{-4} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	0.3
Core Sheath	
Material	4" Mylar Tape 2 mills thick with 45 overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	2.36 W/cm°C
Electrical Conductivity	3.536×10^7 mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	56
Winding Pitch Angle	22°
Shape of Conductors	Round
Size of Conductors	29,464 CM
Percent Fill of Aluminum	75.0
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	.5 mho/m
Specific Gravity	1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	2.36 W/cm^{o}C
Electrical Conductivity	3.536 x 10^{7} mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	67
Winding Pitch Angle	21.9
Shape of Conductors	Round
Size of Conductors	24,627 CM
Percent Fill of Aluminum	74.6
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	2.8 x 10^{-3} W/cm^{o}C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30^{o}C
Thermal Conductivity	5.796 x 10^{-3} W/cm^{o}C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

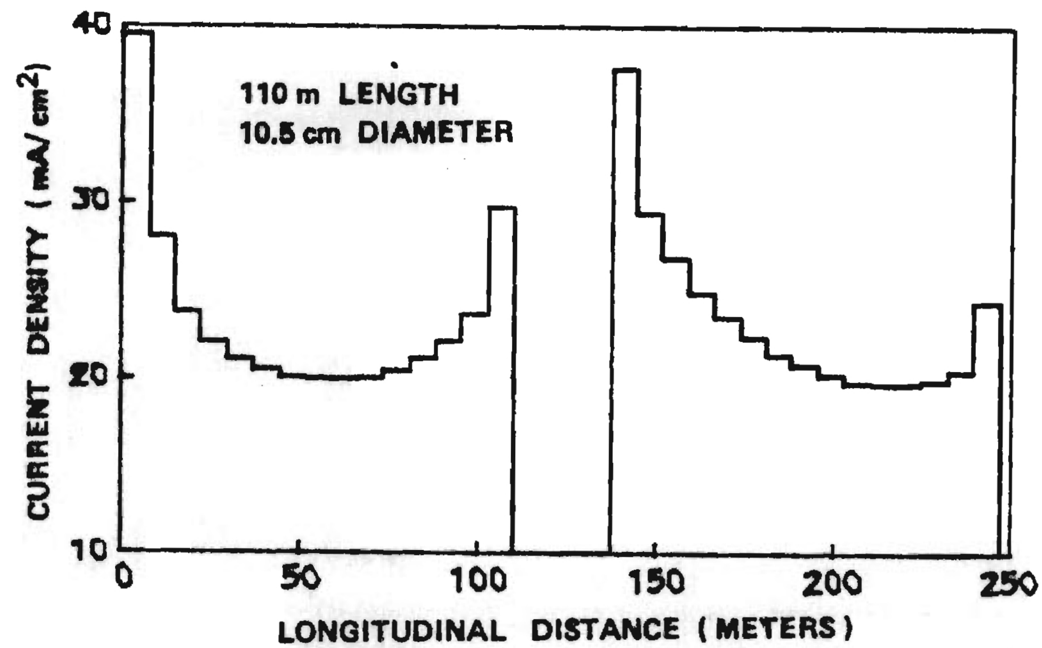


FIGURE 2-9. ANODE & CATHODE RADIAL CURRENT DENSITIES VS. LONGITUDINAL DISTANCE

TABLE 2-III. CONDUCTING JACKET ANODE/CATHODE PARAMETER VALUES

Operational	
Specific Gravity	0.95
Diameter	9.230 cm (3.634 inches)
Length	118 meters (360.9 ft)
Maximum Current	8500 amperes
Maximum Temperature	100.0°C
Maximum System Resistance	15.0 milliohm
Bending Radius	3 feet
Stiffness	4.48×10^4 lb/in^2
Core	
Material(s)	Heat resistance ABS and Silicon Foam
Diameter	7.201 cm (2.835 inches)
Thermal Conductivity	7.53×10^{-4} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	0.3
Core Sheath	
Material	4" Mylar Tape 2 mills thick with 45 overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	0.0 mho/m
Specific Gravity	1.17
Inner Aluminum Layer	
Type of Aluminum	Aluminum Associate 8176 (EEE)
Thermal Conductivity	2.36 W/cm°C
Electrical Conductivity	3.536×10^7 mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	57
Winding Pitch Angle	21.2°
Shape of Conductors	Round
Size of Conductors	21,930 CM
Percent Fill of Aluminum	75.4
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Between Aluminum Layers	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95×10^{-3} W/cm°C
Electrical Conductivity	.5 mho/m
Specific Gravity	1.17

Outer Aluminum Layer	
Type of Aluminum	Aluminum Association 8176 (EEE)
Thermal Conductivity	2.36 W/cm^{o}C
Electrical Conductivity	3.536 x 10^{7} mho/m
Thermal Coefficient	0.56%/C
Specific Gravity	2.7
Number of Conductors	68
Winding Pitch Angle	21.4^{o}
Shape of Conductors	Round
Size of Conductors	18,382 CM
Percent Fill of Aluminum	75.1
Type of Flooding Compound	High Thermal Conductivity Silicone Grease
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	2.0 mho/m
Specific Gravity	1.2
Sheath Over Aluminum	
Material	4" Mylar Tape 2 mills thick with 45% overlap
Thickness	3.8 mills
Thermal Conductivity	2.95 x 10^{-3} W/cm^{o}C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Jacket	
Material	Hytrel Polyester Elastomer 4056
Thickness	0.105 inch $\pm$ .005 inch
Thermal Conductivity	4.23 x 10^{-3} W/cm^{o}C
Electrical Conductivity	0.5 mho/m
Specific Gravity	1.17
Sea Water	
Stagnant Layer Thickness	0.25 mm
Temperature	30^{o}C
Thermal Conductivity	5.796 x 10^{-3} W/cm^{o}C
Electrical Conductivity	4.0 mho/m
Specific Gravity	1.0

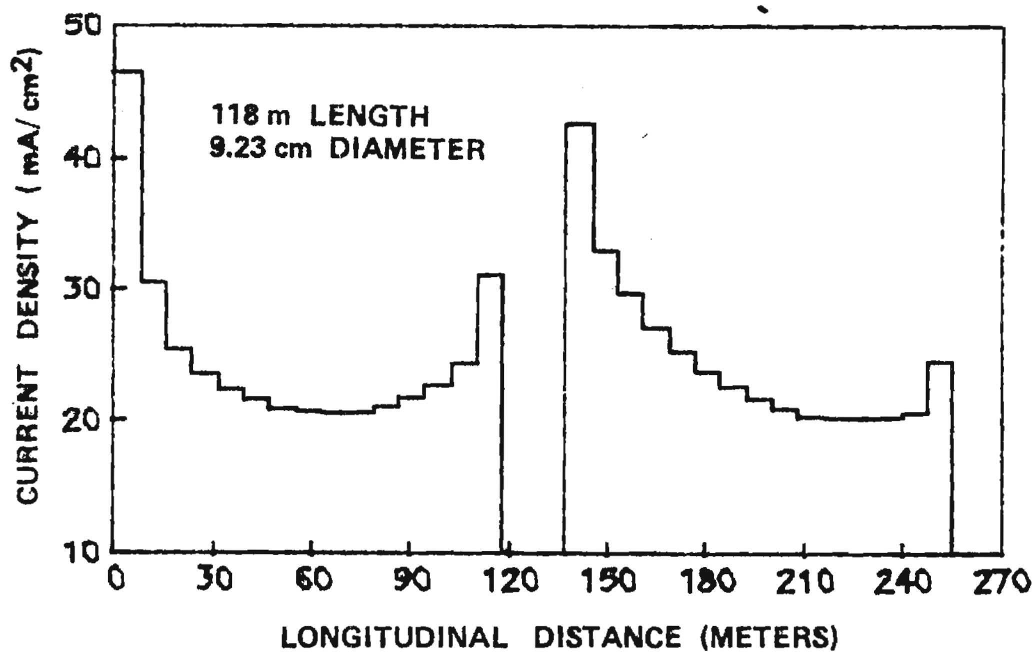


FIGURE 2-10. ANODE & CATHODE RADIAL CURRENT DENSITIES VS. LONGITUDINAL DISTANCE

2.3 Electrochemical Resistance Simulations

The effects of the measured anodic and cathodic electrochemical resistances are simulated and the parameters of the electrodes changed to accomodate the new resistances.

Measurements of the anodic and cathodic electrochemical resistances of the polymer materials resulted in the following imperical equations:

1. Anodic

$$R_E = \frac{3.84 + 2.7 \, \mathrm{Log}_{10}[I(MA/CM^2)]}{I \text{ (Amps)}}$$

2. Cathodic

$$R_E = \frac{0.5 + 3.3 \, \mathrm{Log}_{10}[I(MA/CM^2)]}{I \text{ (Amps)}}$$

Computer simulations showed that these electrochemical resistances were greater than the previously used electrochemical resistances. The anodic resistance for 25 MA/CM^2 is 63 times larger than that for platinum and the cathodic resistance is 2½ times that of aluminum. These increased electrochemical resistances resulted in a 10% increase in system resistance with little effect on temperature. The length of the electrodes must be lengthened to 130 meters to reduce system resistance to 15 milliohms. All other electrode paramenters remained unchanged.

CHAPTER III

TRANSIENT HEAT FLOW ANALYSIS

In order to solve the transient temperature problem for the electrode, the electrode is first divided into a number of sections. A fictitious node is placed at the center of each section. From the geometry of the electrode, it is a one-dimensional problem if the longitudinal heat flow is neglected.

An expression of the conservation of energy for node n is:

$$q_n' + q_{n+1\to n} + q_{n-1\to n} = \frac{\partial U_n}{\partial t} \tag{1}$$

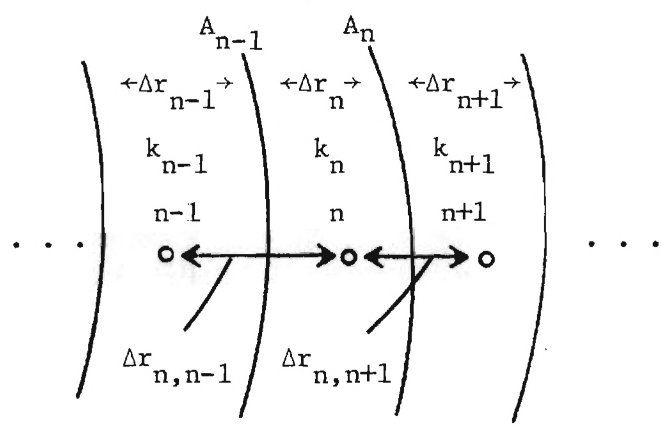
where

q_n' is the heat production of node n,

$q_{n+1\to n}$ is the heat flow from node n+1 to n,

$q_{n-1\to n}$ is the heat flow from node n-1 to n, and

U_n is the internal energy of node n.



If the energy balance equation (1) is written at time t + Δt, it becomes

$$q_n' + k_{n,n-1} A_{n-1}(T_{n-1}^{t+\Delta t} - T_n^{t+\Delta t}) + k_{n,n+1} A_n(T_{n+1}^{t+\Delta t} - T_n^{t+\Delta t})$$

$$= \frac{m_n c_n}{\Delta t} (T_n^{t+\Delta t} - T_n^{t}) \tag{2}$$

where

A_{n-1} is the surface area of the boundary layer between nodes n and n-1,

A_n is the surface area of the boundary layer between nodes n and n+1,

m_n is the mass of node n,

c_n is the specific heat of node n and the equivalent thermal conductivity $k_{n,m}$ is given by

$$k_{n,m} = \frac{\dfrac{k_n}{(\Delta r\ n/2)} \cdot \dfrac{k_m}{(\Delta r\ m/2)}}{\dfrac{k_n}{(\Delta r\ n/2)} + \dfrac{k_m}{(\Delta r\ m/2)}} \tag{3}$$

The mass of node n, m_n, is given by

$$m_n = 2\pi \rho_n r_n \Delta r_n \ell \tag{4}$$

where

ρ_n = density of n^{th} node

r_n = center radius of n^{th} node

ℓ = length of the electrode

If the boundary between two nodes involves convection instead of conduction which was the case in Eq. (2), a new energy balance equation must be used. An example of energy balance equation with convection between nodes n and n-1 and conduction between nodes n and n+1 is

$$q_n' + \bar{h}_c A_{n-1}(T_{n-1}^{t+\Delta t} - T_n^{t+\Delta t}) + k_{n,n+1} A_n(T_{n+1}^{t+\Delta t} - T_n^{t+\Delta t})$$

$$= \frac{m_n c_n}{\Delta t}(T_n^{t+\Delta t} - T_n^{t}) \tag{5}$$

where $\bar{h}_c$ is the convective heat transfer coefficient (or, equivalently, thalpance).

The Eqs. (2) and (5) are of the same form; thus a problem involving both conduction and convection may be expressed in a single matrix equation. Now, Eq. (2) can be rewritten as

$$\frac{\Delta t\ k_{n,n-1} A_{n-1}}{m_n c_n}(T_{n-1}^{t+\Delta t} - T_n^{t+\Delta t}) + \frac{\Delta t\ k_{n,n+1} A_n}{m_n c_n}(T_{n+1}^{t+\Delta t} - T_n^{t+\Delta t})$$

$$= T_n^{t+\Delta t} - T_n^{t} + \frac{\Delta t}{m_n c_n} q_n' \tag{6}$$

Multiplication to both sides of Eq. (6) by -1 and addition of $T_n^{t+\Delta t}$ yields

$$-\left(\frac{\Delta t\ k_{n,n-1} A_{n-1}}{m_n c_n}\right) T_{n-1}^{t+\Delta t} + \left(1 + \frac{\Delta t\ k_{n,n+1} A_n}{m_n c_n} + \frac{\Delta t\ k_{n,n-1} A_{n-1}}{m_n c_n}\right) T_n^{t+\Delta t}$$

$$-\left(\frac{\Delta t\ k_{n,n+1} A_n}{m_n c_n}\right) T_{n+1}^{t+\Delta t} = T_n^{t} + \frac{\Delta t}{m_n c_n} q_n' \tag{7}$$

Eq. (7) in a simplified form is

$$a_{n,n-1} T_{n-1}^{t+\Delta t} + a_{n,n} T_{n}^{t+\Delta t} + a_{n,n+1} T_{n+1}^{t+\Delta t} = T_n^{\,t} + \frac{\Delta t \, q_n'}{m_n c_n} \qquad (8)$$

Eq. (8) in a matrix form is shown in Eq. (9) on the following page.

All the elements in matrix [A], except the main and the adjacent diagonal elements, are zero. It is called a tridiagonal matrix for which there are efficient algorithms to solve for [T].

In matrix [B], there are two unknown terms $T_o^{t+\Delta t}$ and $T_{N+1}^{t+\Delta t}$. However, if the node thicknesses are small compared to the diameter of the electrode and if the time interval is small, the following approximations hold.

$$T_1^{\,t} \cong T_o^{t+\Delta t} \qquad (10)$$

$$T_N^{\,t} \cong T_{N+1}^{t+\Delta t} \qquad (11)$$

Eq. (9) can now be rewritten as Eq. (12) on the following page.

The temperature of i^{th} node at time t+ t, $T_i^{t+\Delta t}$, can be calculated by solving the above system of simultaneous equations, and by iterating the procedure, temperatures at later times can be calculated.

$$\underbrace{\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1N} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2N} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3N} \\ \vdots & & & \ddots & \vdots \\ a_{N1} & a_{N2} & a_{N3} & \cdots & a_{NN} \end{bmatrix}}_{[A]} \underbrace{\begin{bmatrix} T_1^{t+\Delta t} \\ T_2^{t+\Delta t} \\ T_3^{t+\Delta t} \\ \vdots \\ T_N^{t+\Delta t} \end{bmatrix}}_{[T]} = \underbrace{\begin{bmatrix} T_1^{t} + \dfrac{\Delta t \; q_1'}{m_1 C_1} + a_{10} T_o^{t+\Delta t} \\ T_2^{t} + \dfrac{\Delta t \; q_2'}{m_2 C_2} \\ T_3^{t} + \dfrac{\Delta t \; q_3'}{m_3 C_3} \\ \vdots \\ T_N^{t} + \dfrac{\Delta t \; q_N'}{m_N C_N} + a_{N,N+1} T_{N+1}^{t+\Delta t} \end{bmatrix}}_{[B]} \qquad (9)$$

$$
\begin{bmatrix}
a_{11} & a_{12} & 0 & 0 & \cdots & \cdots & \cdots & 0 \\
a_{21} & a_{22} & a_{23} & 0 & \cdots & \cdots & \cdots & 0 \\
0 & a_{32} & a_{33} & a_{34} & 0 & \cdots & \cdots & 0 \\
0 & 0 & a_{43} & a_{44} & a_{45} & 0 & \cdots & 0 \\
\vdots & & & & \ddots & & & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 \cdots & a_{N,N-1} & a_{NN}
\end{bmatrix}
\begin{bmatrix}
T_1^{t+\Delta t} \\
T_2^{t+\Delta t} \\
T_3^{t+\Delta t} \\
T_4^{t+\Delta t} \\
\vdots \\
T_N^{t+\Delta t}
\end{bmatrix}
=
\begin{bmatrix}
(1+a_{10})T_1^{\,t} + \dfrac{\Delta t\ q_1'}{m_1 c_1} \\
T_2^{\,t} + \dfrac{\Delta t\ q_2'}{m_2 c_2} \\
T_3^{\,t} + \dfrac{\Delta t\ q_3'}{m_3 c_3} \\
T_4^{\,t} + \dfrac{\Delta t\ q_4'}{m_4 c_4} \\
\vdots \\
(1+a_{N,N+1})T_N^{\,t} + \dfrac{\Delta t\ q_N'}{m_N c_N}
\end{bmatrix}
\qquad (12)
$$

Following are some significant computed results using the above equations and algorithm for transient thermal analysis. Figure 3-1 shows the temperature distribution in the electrode and sea water as the electrode moves rapidly through the sea water at ambient temperature of $30^{o}C$; and at time = 0, the current is suddenly turned on. This figure shows that the aluminum layers which are in the 4.14-4.99 cm radius range reach full temperature within 30 minutes, while the core requires approximately 90 minutes to reach full temperature. The jacket which extends from 4.99 to 5.27 cm has an approximately linear temperature distribution spanning the entire range from maximum to sea water temperature. Maximum temperature at full current is seen to be less than $100^{o}C$ after 90 minutes.

Figure 3-2 shows the temperature distribution in the electrode and the sea water when the electrode is not moving; and at time = 0, the current is suddenly turned on. The aluminum layers reach a temperature of approximately $200^{o}C$ in 30 minutes when operating under no speed conditions. It is estimated from this figure that the electrode could be operated under no speed condition, at full current for 9 minutes (starting from sea water temperature) without damage to the electrodes.

Figure 3-3 shows the temperature distribution in the electrode and the sea water as the electrode, which has been moving rapidly at operating temperature, suddenly stops moving at time = 0 with full current still on. This figure shows the rapid temperature rise of the surface of the electrodes and outer portions of the jacket material.

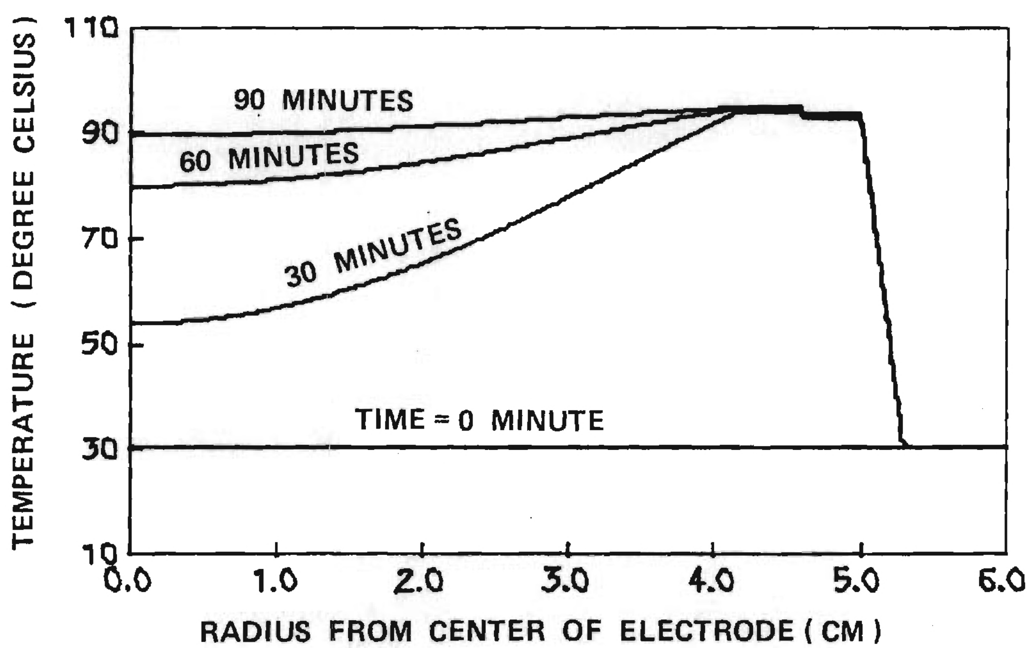


FIGURE 3-1. ELECTRODE AND SEA WATER TEMPERATURE VS. RADIUS AT HIGH SPEED

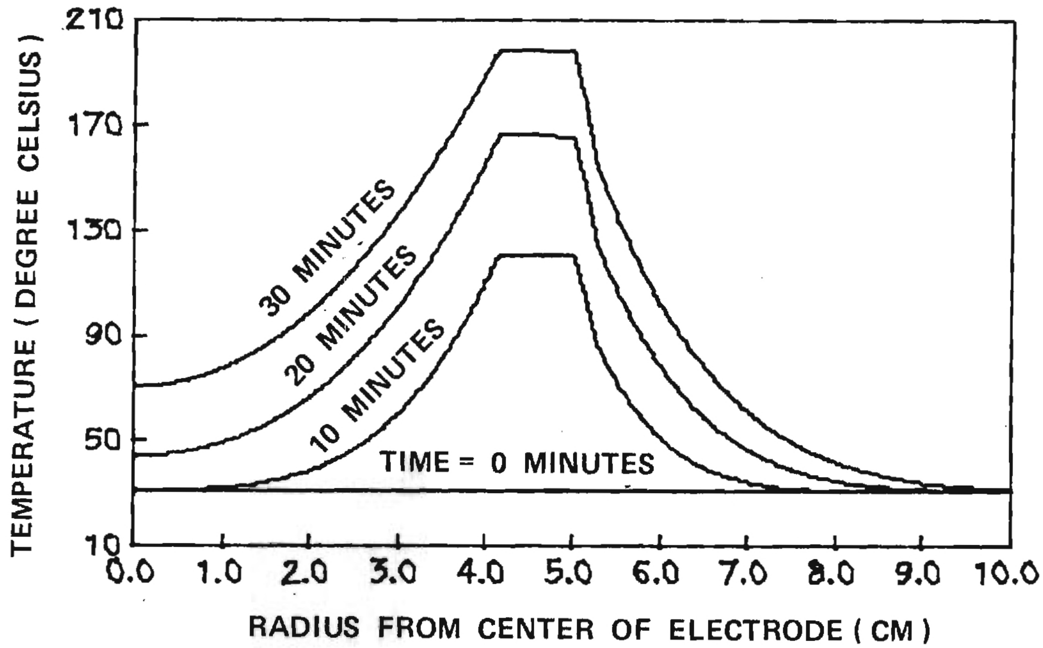


FIGURE 3-2. STATIONARY ELECTRODE AND SEA WATER TEMPERATURE VS. RADIUS

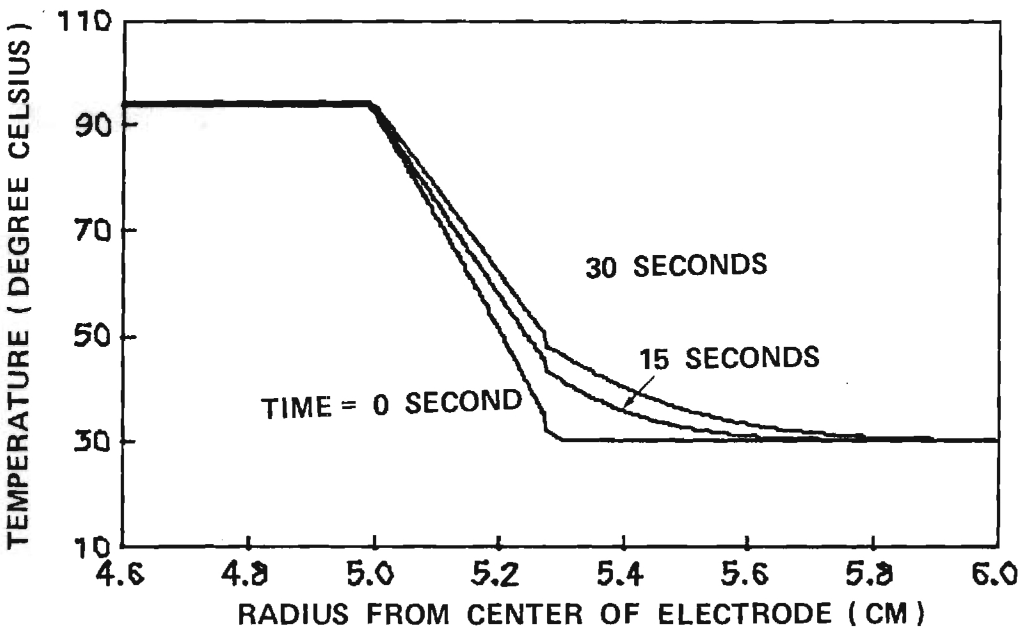


FIGURE 3-3. ELECTRODE AND SEAWATER TEMPERATURE VS. RADIUS FOR SUDDEN STOP

Figure 3-4 shows the temperature of the inner aluminum layer of the electrodes versus time since application of minesweeping current. The electrodes used in this analysis are the same as described in the previous chapter. Four current levels are shown. This figure suggests that large current levels can be used for short pulses (pulses of duration less than 5 minutes, depending on current level) without exceeding 100 degrees celsius. However, the time average current must still be equal to or less that the design current.

The above conclusions are based solely on thermal considerations. Electrochemical considerations show that the lifetime of an electrode is shortened by large current pulses as this increases current density and accelerates jacket deterioration.

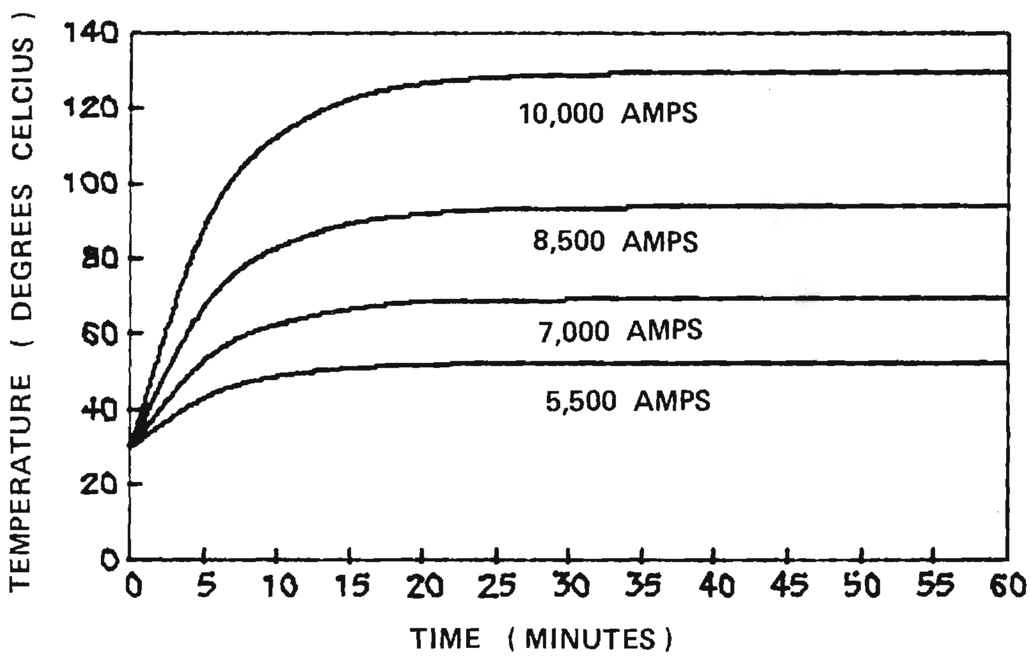


FIGURE 3-4. ELECTRODE CONDUCTOR TEMPERATURE VS. TIME FOR DIFFERENT SWEEP CURRENTS

CHAPTER IV

NON BUOYANT ELECTRODE

A computer algorithm was developed for the electrical, mechanical and thermal analysis of non buoyant electrodes. This algorithm was used to generate preliminary parameter values for a 1000 MCM copper, non buoyant electrode system using a standard 450 foot S-cable. The anode and cathode are each 200 feet long and have an .105 inch thick high conductivity Hytrel jacket. Table 4-I gives the preliminary parameters for each electrode.

TABLE 4-I. NON BUOYANT ELECTRODE PARAMETERS

OVERALL:

Length:	60.96 meters
Diameter:	4.012 centimeters

CORE:

Material:	Copper
Electrical Conductivity:	5.8×10^7 mho/meter
Thermal Conductivity:	4.03 W/cm C^o
TOTAL CONDUCTOR SIZE:	1×10^6 circular mils
Number of Conductors:	2280
Size of Each Conductor:	438.6 circular mils

Layering:

Bundle Parameters:

Layer	No. of Conductors	Winding Pitch
1	1	0^o
2	6	0^o
3	12	15^o

Layer Parameters:

Layer	No. of Bundles	Winding Pitch
1	1	0^o
2	5	31.3^o
3	11	26.5^o
4	17	23.2^o
5	23	20.9^o
6	29	19.1^o
7	34	22.1^o

SHEATH:

Material:	Mylar Tape
Thickness:	.1016 millimeters
Thermal Conductivity:	2.95×10^{-3} W/cm C^{o}
Electrical Conductivity:	.5 mho/meter

JACKET:

Material:	High Conductivity Hytrel
Thickness:	2.67 millimeters
Thermal Conductivity:	4.3×10^{-3} W/cm C^{o}
Electrical Conductivity:	.5 mho/meter

SEA WATER:

Thickness of Electrochemical Layers:	.25 millimeter
Thermal Conductivity:	5.8×10^{-3} W/cm C^{o}
Electrical Conductivity:	4 mho/meter

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

A. The optimum combination of electrical and mechanical properties for a Hytrel 4056 base conductive polymer is achieved with 20% to 22% KJB carbon and 2% PCD stabilizer.

B. Lower electrochemical life was the result of poorer control on pilot trial manufacturing scale processing variables, particularly time and temperature. The more stringent electrochemical test also accounts for a lower life. Further analysis will be available on the small test scale samples being supplied NCSC on this contract.

C. Improved electrochemical life can be achieved with more controlled processing and more controlled processing is possible on specialized compounding equipment available at the Banbury Company in New Jersey. This company will allow us to rent their facilities for short term special compounding tests.

D. A computer program was developed for the transient thermal analysis of high current DC electrode systems. Simulations conducted using the algorithm show that pulsed operation is possible and show limited operation with no speed is possible.

E. A computer algorithm was developed for the analysis of non buoyant electrode systems and preliminary parameters for a 200 foot electrode were generated.

F. The new high thermal conductivity electrode jacket allowed an electrode design which was 60% more flexible and had 6% less drag than previous designs.

G. The electrochemical resistances of the high conductivity Hytrel material were found to be higher than metal electrodes and resulted in a 10% increase in electrode length and drag. Thus the overall effect of high thermal conductivity and high electrochemical resistance was an electrode which is 60% more flexible and has 4% higher drag than previous conductivity polymer electrodes.

H. It is estimated that the cost of factory replacement of a conducting polymer jacket is approximately equal to the cost of the aluminum for the replacement of the aluminum on an equivalent aluminum electrode.

5.2 RECOMMENDATIONS:

A. Intensive study of Hytrel base materials should be performed under highly controlled manufacturing type compounding in a commercial twin screw mixer available for time rental from the Banbury Company in New Jersey. This equipment will allow shorter processing time, better mixing and finer control of temperature. Such tests should come closer to the best patented compound in this system.

B. Other alternatives should also be explored to improve compounding.

   1) A lower viscosity Hytrel (DuPont 5526) to allow lower temperature mixing;

   2) Other stabilizers, to determine if a higher temperature stabilizer is available;

   3) Look at the potential of adding some regular graphite to the mixture, not for conductivity but to improve the lubrication qualities of the material which will allow extrusions at slightly lower temperatures.

All of these factors should help eliminate deterioration of the Hytrel and stabilizer during compounding. This should give longer electrochemical life.

C. Pt or Pd coated Nb strips or mesh should be imbedded in the conductive polymer jacket surface using the noble surface for the electrochemical reaction and conduction from the inner core occurring through conductive jacket. Trial results showed potential life >200 hours and possibly much greater when developed. Although the mechanical properties are slightly less than Hytrel, the urethane rubbers (such as Estane 58863) should be examined because these polyether based elastomers have a hydrolytic stability that is inherently superior to the polyester based elastomers, such as Hytrel.

D. The trade off between electrode length and submergence to achieve lower resistance and drag should be investigated.

APPENDIX I

RESULTS OF TENSILE TESTS ON COMPOUNDED STABILIZED HYTREL-CARBON

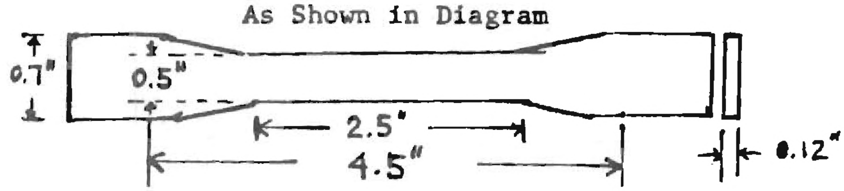
TENSILE PROPERTIES OF HYTREL

MATERIAL: Hytrel 4056, Sample Extruded

KJB: 20%

PCD 1%

DIMENSION: As Shown in Diagram



TEST CONDITION: Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:	Sample 1	2850 psi, Unbroken	
	2	3310 psi, Unbroken	
	3	3310 psi, Unbroken	
	Standard Deviation: 270 psi		
PERCENTAGE ELONGATION:	Sample 1	420% + Unbroken	
	2	420% + Unbroken	
	3	420% + Unbroken	
	Standard Deviation: 0%		
YOUNG'S MODULUS:	Sample 1	22500 psi	
	2	20800 psi	
	3	20200 psi	
	Standard Deviation: 1200 psi		

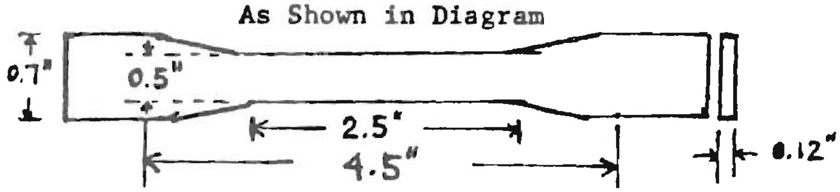
TENSILE PROPERTIES OF HYTREL

MATERIAL: Hytrel 4056, Sample Extruded

KJB: 20%

PCD: 2%

DIMENSION: As Shown in Diagram



TEST CONDITION: Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

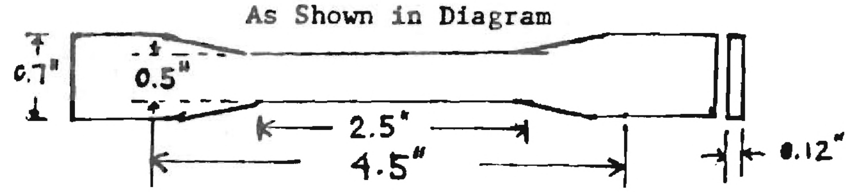
ULTIMATE TENSILE STRENGTH:	Sample 1	2970 psi, Unbroken	
	2	3170 psi, Unbroken	
	3	2150 psi, Defective*	
	Standard Deviation: 140 psi		
PERCENTAGE ELONGATION:	Sample 1	400% + Unbroken	
	2	420% + Unbroken	
	3	260% Defective*	
	Standard Deviation: 14%		
YOUNG'S MODULUS:	Sample 1	27100 psi	
	2	24200 psi	
	3	24200 psi *	
	Standard Deviation: 1700 psi		

*Not counted in the average

TENSILE PROPERTIES OF HYTREL

MATERIAL:	Hytrel 4056, Sample Extruded	
	KJB:	21%
	PCD:	1%

DIMENSION: As Shown in Diagram



TEST CONDITION:

Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:

Sample	1	2920 psi
	2	2350 psi
	3	2850 psi

Standard Deviation: 310 psi

PERCENTAGE ELONGATION:

Sample	1	400%
	2	260%
	3	380%

Standard Deviation: 76 %

YOUNG'S MODULUS:

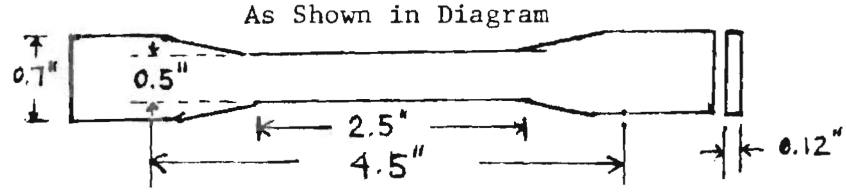
Sample	1	26000 psi
	2	20800 psi
	3	20800 psi

Standard Deviation: 3000 psi

TENSILE PROPERTIES OF HYTREL

MATERIAL:	Hytrel 4056, Sample Extruded	
	KJB:	21%
	PCD:	2%

DIMENSION: As Shown in Diagram



TEST CONDITION:

Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:

Sample 1	2380psi
2	2800psi
3	3230psi

Standard Deviation: 430psi

PERCENTAGE ELONGATION:

Sample 1	380%
2	270%
3	380%

Standard Deviation: 64%

YOUNG'S MODULUS:

Sample 1	34600psi
2	26000psi
3	20800psi

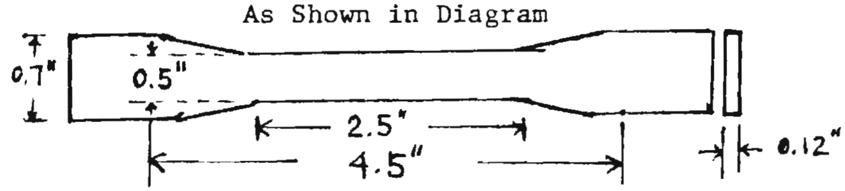
Standard Deviation: 7000psi

TENSILE PROPERTIES OF HYTREL

MATERIAL: Hytrel 4056, Sample Extruded

KJB:	22%
PCD:	1%

DIMENSION: As Shown in Diagram



TEST CONDITION:

Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:

Sample 1	2580psi
2	2300psi
3	2800psi

Standard Deviation: 250psi

PERCENTAGE ELONGATION:

Sample 1	380%
2	340%
3	340%

Standard Deviation: 23%

YOUNG'S MODULUS:

Sample 1	20800psi
2	20800psi
3	28800psi

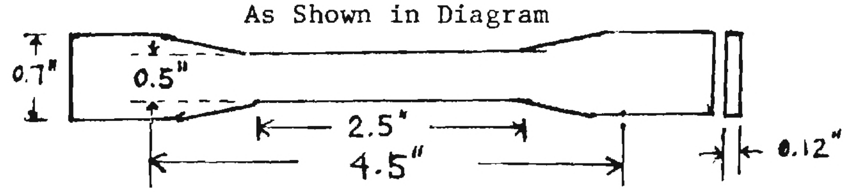
Standard Deviation: 4600psi

TENSILE PROPERTIES OF HYTREL

MATERIAL: Hytrel 4056, Sample Extruded

KJB:	22%
PCD:	2%

DIMENSION: As Shown in Diagram



TEST CONDITION:

Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:

Sample 1	2650psi
2	2960psi
3	--

Standard Deviation: 220psi

PERCENTAGE ELONGATION:

Sample 1	280%
2	370%
3	---

Standard Deviation: 64%

YOUNG'S MODULUS:

Sample 1	20800psi
2	24200psi
3	--

Standard Deviation: 2400psi

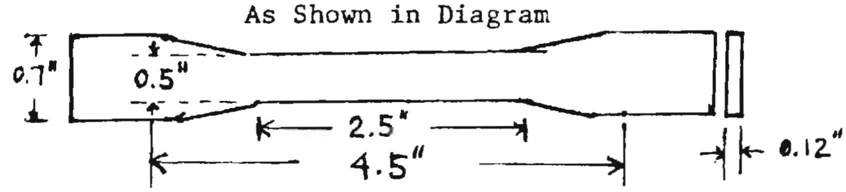
TENSILE PROPERTIES OF HYTREL

MATERIAL: Hytrel 4056, Sample Extruded

KJB: 22%

PCD: 2%

DIMENSION: As Shown in Diagram



TEST CONDITION: Room Temperature, 25°C

Strain Rate = 0.44 min^{-1}

Cross Head Speed = 2 in./min.

Chart Speed = 2 in./min.

ULTIMATE TENSILE STRENGTH:

Sample 1	2650psi
2	2960psi
3	--

Standard Deviation: 220psi

PERCENTAGE ELONGATION:

Sample 1	280%
2	370%
3	---

Standard Deviation: 64%

YOUNG'S MODULUS:

Sample 1	20800psi
2	24200psi
3	--

Standard Deviation: 2400psi